

Exploring NASA Human Spaceflight and Pioneering Scenarios

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It is possible and desirable to consider many NASA human spaceflight scenarios, along with all their elements, within a long-term NASA budget context. While there is an abundance of cost analysis of specific space system elements in a narrow context or performance analysis of broad scenarios with no NASA budget context, approaches that balance the details in-hand alongside a NASA budget context across possible scenarios have been absent.

This situation is not for lack of enough data, understanding, cost models or mission definition. Uncertainty in selecting or having a mandate for a specific spaceflight direction should not be cause to avoid looking at any scenarios at all, especially if many very different scenarios can be analyzed rather well. Insufficient emphasis on a NASA budget context as an input into long term planning, the treatment of budgets and schedules as an output of proposed initiatives, rather than an input, and a lack of understanding of NASA budget-nuances likely all contribute to the lack of life cycle cost analysis for spaceflight scenarios.

Given the importance of a NASA budget context, life cycle cost modeling and analysis for NASA's spaceflight pioneering investments cannot afford to ignore where or who and the types of money in the NASA budget. Similarly, valuing situational awareness, it is not advantageous or necessary to await a specific mandate or decision only to analyze slight variations on that single directions life cycle costs later. This is akin to being in the wilderness, but refusing to explore your surroundings until after a decision on which way to go -and then proceeding strictly in that direction. Rather, reconnaissance in many directions is valuable, feedback on which way to go, regardless of uncertainty about eventual choices.

The modeling and analysis here will show that it is not necessary to define every part of every possible space exploration scenario in order to gain valuable insights. A scenario planning approach that explores many life cycle possibilities is valuable and feasible, by combining the more defined space system elements alongside a thorough understanding of NASA budgets as context. This provides defined and valuable insights for "that which remains". A scenario exploration strategy of "that which remains" takes the more defined elements, places these into potential, but defined, budget scenarios, and outputs valuable insights for the less defined elements. From this process, the necessary affordability and productivity characteristics of "that which remains" are refined. In addition, the understanding of the scenario as a whole improves. This paper presents such an approach, via cost modeling and analysis, reviewing many space exploration scenarios within a NASA

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budget and inflation context, a purchase power context, with a detailed understanding of NASA-speak and NASA practice in properly accounting for all costs.

Scenarios where the International Space Station (ISS) ends and those where the ISS does not end in the scenarios horizon are considered. Within this backdrop, scenarios include: potential reusable launch vehicles (Falcon 9-Reusable and others), existing expendable launch vehicles (Falcon 9, Delta IV Heavy), potential space transportation systems in development (the Space Launch System, the Falcon Heavy), potential spacecraft in development (Orion, Commercial Crew, future variants, etc.), and potential in-space infrastructure (for in-space refueling of Earth departure stages) for lunar, asteroid and Mars exploration scenarios. Important links between what and how, technical and non-technical factors, and how these affect costs, are shown. Given budgetary pressures, it is no longer possible to ignore non-technical drivers of industry / partner costs as has been past practice in cost modeling. Commercial space scenarios are explored at many levels, where “how” a system is acquired by NASA and developed and made by industry partners, existing or emerging, is as important as “what” is delivered or provided. Processes and practices by industry partners, from business-as-usual to improved “best practices” established in non-aerospace, but complex, applications, are shown as crucial to scenarios that further NASA’s space exploration efforts.

A sampling of the many scenarios that can be explored with the cost model are presented in this paper. The cost model will also be reviewed, one part being a launcher focused cost model, another being a broader exploration systems scenario cost model. Non-recurring development, recurring manufacturing, and recurring operations across multiple elements, from flight to ground systems, from launch, to in-space elements, to surface systems, are addressed. Graphical results and the insights from these are presented - a reference for the possible life cycle costs and implications of many scenarios, element by element, across life cycle phases.

Nomenclature

<i>COTS</i>	= Commercial Orbital Transportation Services
<i>CPS</i>	= Cryogenic Propulsion Stage
<i>CRS</i>	= Cargo Resupply Services
<i>DOD</i>	= Department of Defense
<i>EDS</i>	= Earth Departure Stage
<i>EUS</i>	= Exploration Upper Stage
<i>HEO</i>	= Human Exploration and Operations
<i>ICPS</i>	= Interim Cryogenic Propulsion Stage
<i>ISRU</i>	= In-situ Resource Utilization
<i>ISS</i>	= International Space Station
<i>LCC</i>	= Life Cycle Cost
<i>LEO</i>	= Low Earth Orbit
<i>LH2</i>	= Liquid Oxygen
<i>LOX</i>	= Liquid Hydrogen
<i>LSP</i>	= Launch Services Program
<i>R&D</i>	= Research and Development
<i>SCaN</i>	= Spacecraft Communications and Navigation
<i>SFS</i>	= Space Flight Support
<i>SLS</i>	= Space Launch System
<i>STMD</i>	= Space Technology Mission Directorate

I. Introduction

Three factors drive the development of quantifiable NASA human spaceflight scenarios looking to the next decade - the key word being “quantifiable” and referring to life cycle costs. Of course, choices, pressures, technical and non-technical factors (economics, demographics, politics, societal trends and constraints, etc.) will affect specific content, but all the content and their interactions will manifest itself inside broad scenarios that are all about context. The three factors driving scenarios as context are:

- 1) The growth rate of the NASA budget
- 2) The rate of cost inflation for the aerospace goods and services NASA acquires
- 3) The future of the International Space Station (ISS), or more broadly, the degree to which a human presence in low Earth orbit (LEO) persists in the NASA portfolio

Any quantified life cycle costs (LCC) for any NASA human spaceflight scenario will live, so to speak, inside a box the sides of which are a scenario set by variations of the prior three factors. Any architecture, launch rate, space systems elements, schedules, goals, or achievements, the milestones of progress and relevance, will reside inside a “budget” X “inflation” X “future NASA LEO presence” box.

While other smaller factors in the NASA budget mix, and their resources, could act in combination to heavily influence the context in which future NASA space exploration scenarios beyond Earth orbit will dwell, it is the three factors listed that will prove most significant in the next decade acting individually as well as in combination.

II. The NASA Budget, Inflation and the Last Decade

Figure 1 shows the NASA budget since 2003. Transitions and markers indicate significant changes in the placement of NASA resources related to changes in direction and events.

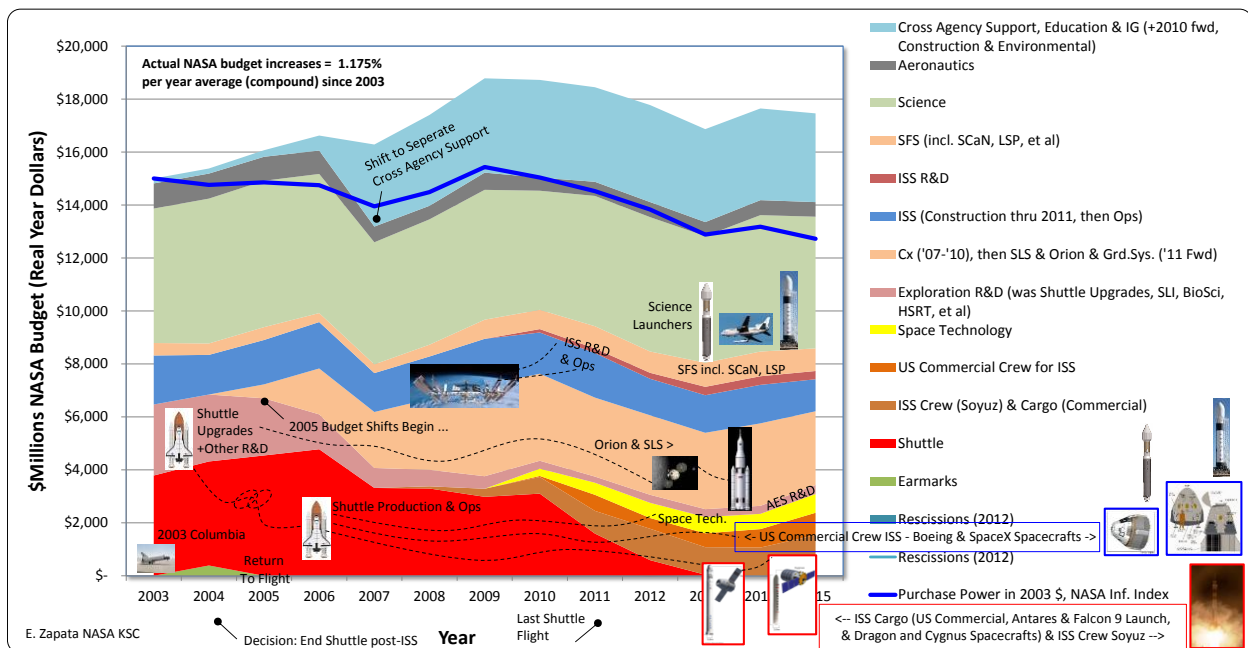


Figure 1. The NASA budget since 2003. Transitions in accounting, the start and end of major programs, and the movement of resources for new capabilities, alongside a consideration of inflation.

Because the availability of resources is so critical to future spaceflight scenarios, it's worth highlighting some key observations that come from visualizing the NASA budget data (“actuals” as they are called) within this specific sand chart. This is necessary as we set the table for diverse, specific NASA space exploration scenarios ahead. Dispelling myths and more accurately predicting the behavior, limitations and nature of the budget box for future scenarios is another purpose in reviewing the NASA budget from the past decade as we look ahead at the next.

Significant budget observations, significant because of their usefulness for future planning purposes, supported by the data in Figure 1, include-

- 1) **The importance of developing a proper context about future NASA budget shifts:** In the aftermath of the decision to end the Space Shuttle program, a general sense that 100% of the Space Shuttle funds would be available to what-ever came after would have been woefully incorrect. Yet such a notion did arise at the policy level¹. What was missing was context. For one, context that the ISS would still require US cargo, crew and their launch support, meaning budget resources. Second, that the date of the end of the ISS program was beyond the then current political-cycle, and soon (six years, or 2016) after construction would have been declared complete (2010). That is to say, the scenario for freeing up Shuttle *and* ISS funds totally, for planning purposes, was beyond uncertain, unstudied and destined to be incorrect.
- 2) **The importance in large program transitions of seeing standing capabilities in NASA that may not be readily apparent:** Large-scale NASA programs may carry standing capabilities within their own books. This goes unnoticed until that program ends. Then, NASA provides resources to the standing capability, perhaps from new programs. The dollars received by the new program are now less than expected, less than might have been advertised for the new programs planning purposes (and to planning people). By way of analogy, though as much about labor as infrastructure, if sounding like too much NASA-speak (or accountants hiding off shore bank accounts), if you are keeping a large property, and the main tenant leaves, the costs of maintaining the large building may remain as high as when fully occupied. One example of this is visible in Figure 1 in the “SFS (incl. SCaN, LSP, et al.)” item. Notice how the thickness of the sand for this item, its budget, goes significantly up after the end of the Shuttle program. The cost of many Space Flight Support (SFS) functions was always there. No new cost appeared, just that this line item had many resources book-kept under the Shuttle program. That cost was just more apparent once it stepped out from under the Shuttle programs budget umbrella. Other areas in NASA, like “Cross Agency Support”, are also standing capabilities, but accounting changes separated these since 2007 precisely to provide clarity.

The budget graph, in its raw data, reveals-

- 1) **NASA’s budget has increased on average 1.175% per year since 2003.** That is, taking the 2003 NASA budget, and increasing it at 1.175% yearly, including compounding, yields the 2015 NASA budget.
- 2) **NASA’s purchasing power has declined 15% from 2003 to 2015.** Using the official NASA Inflation Index² yields a 15% decline in NASA’s purchasing power from 2003 to 2015. Given the lack of certainty about something as complex as cost inflation across so many different projects, products and organizations, alternative scenarios about what may be happening here will be explored ahead.
- 3) **The end of the operational portion of NASA’s Space Shuttle program freed up for other purposes \$860M in 2013, two years after the Shuttle last flight, and less, \$360M a year by 2015.** The nuanced words here in saying that little, if any, Shuttle operations funding was actually freed up to other purposes after the end of the Shuttle program are the words “operational” and “other purposes”. The funding of a new program line, the Constellation program, later the Space Launch System (SLS), Orion and the Ground Operations project, received budget resources since 2005 mostly from the more immediate end of the Space Shuttle’s standing capability development, “upgrades” and related investment budgets. There was no further need to fund investments in Shuttle improvements because it was already a decision that the Shuttle would fly only until it completed the ISS construction. Specific “operational” space transportation funds from the Shuttle have remained as “operational” space transportation funds for the ISS – almost to the dollar, per official, public NASA budget documents³. These became the ISS Crew (Soyuz) & Cargo (Commercial), and US Commercial Crew programs.

More NASA budget and cost inflation scenarios lie ahead. Scenarios range from the nominal, where budgets go up in the future just as they have historically, and using an official NASA Inflation Index for costs, to where conditions may be more optimistic or pessimistic, and why.

[‡] Notably, any measure of funds alone is incomplete without considering improvements in the flexibility with which the funds can be applied; a service model by way of example having an ability to buy-by-the-yard, unlike an acquisition model more akin to ownership, including fixed, less flexible, long term commitments and costs. The private sector refers to this as supply chain flexibility, measuring the ability of a supply chain to adjust costs up or down as requirements change.

III. The Future of ISS and NASA's Presence in Low Earth Orbit

After budgets and inflation, the third factor that will significantly affect the sides of a scenarios box, the context into which future NASA exploration scenarios will or will not fit well, is the future of the ISS. As of 2014, NASA and the current administration have committed to “an extension of the International Space Station (ISS) until at least 2024.”³⁷

As with the decision to end the Space Shuttle program, planners might again be tempted to take all the ISS related layers of sand in Figure 1, the US commercial cargo and crew services, ISS research and development (R&D), and the ISS operations funds, and put these amounts 100% toward plans for the next big thing. Two considerations must give this pause. One, the experience with the end of the Space Shuttle program showed that budgets might not be what they appear to be, that caution, context and a proper understanding of the inner workings of any budget lines is necessary. Second, the NASA associate administrator for human spaceflight, William H. Gerstenmaier, has already indicated that even were the ISS to end in 2024, a NASA's presence in low Earth orbit will not. Rather (quote) “*we can just buy these services*”³⁸ from private sector space stations. As NASA's presence in LEO would not end after the end of the ISS, even the temptation to show a diversion of ISS related budgets after some date could not reasonably begin with planning for 100% of funds becoming available for other uses.

With the previous cautions in mind, delving into the ISS budget lines (2015) finds-

- | | |
|---|------------------------|
| 1) ISS Operations | ~ \$1.2 billion a year |
| 2) ISS R&D, the use of the ISS | ~ \$300 million a year |
| 3) ISS Cargo & Crew, Transportation and Related | ~ \$2.4 billion a year |
| Total International Space Station = | ~ \$3.9 billion a year |

Learning from the Shuttle program ending, and its experience, names may not be as telling as they appear. First, the ISS operations are in some portion the task of any NASA in-space operations, mission control and mission operations, performed mostly at the Johnson Space Center. There would be reason to be cautious about how much of this funding would be available for post-ISS programs (including the possibility –very little).

Second, considering partnerships with the private sector for a continued low Earth orbit NASA presence (Figure 2), buying services from private sector space stations, an immediate question would be how to get NASA astronauts to these private stations. Would the private sector space station bundle the ride, and cargo arrangements along with the person-hours of time NASA is buying (as if renting, rather than owning)? Any consideration of what happens to the largest ISS budget line item, the \$2.4 billion a year to get US crew and their cargo to the station would have to address how far such transport costs to NASA may have improved, a space transportation cost that could be unrelated to the progress of private space stations. By way of considering scenarios, would a reduction in the number of NASA astronauts at a private station, and a minor improvement in crew and cargo launch costs, mean cargo and crew transportation costs drop 50%? That would mean \$1.2 billion a year in a post-ISS / private space stations scenario that (for just this one line item of the total ISS costs) would be unavailable to future programs in that post-ISS world.

It is not difficult to envision post-ISS scenarios that yield very low, nominal and high amounts of post-ISS funding for projects that follow. The ISS budget numbers when understood, self-describe the conditions necessary to count funds more or less towards future NASA projects. Some of these conditions will sound very reasonable, others less so.

More post-ISS scenarios lie ahead[§]. Scenarios range from the nominal, as regards a 2024 planning date for an end-of-ISS budget transition to start, to the off nominal (“when” may be 2028⁵), with variations on how budgets may or may not free up, where and why - for future projects such as Mars exploration.

[§] Scenarios for ISS cost improvements in the near term, reduced ISS and related budgets at the same capability or greater than current, but before 2024, are not considered here, for lack of any NASA statements to-date on this regard. This possibility may arise naturally as part of post-ISS planning, as well as in forward work building on the merger of scenarios and analysis here.



Figure 2. The Bigelow Expandable Activity Module (BEAM). In 2015, a mission to the ISS will attach this module, demonstrating technology for future space stations. (Public domain photo; http://en.wikipedia.org/wiki/Bigelow_Expandable_Activity_Module#/media/File:BEAM_press_conference_01.jpg)

IV. NASA Human Exploration & Operations

Figure 3 will be the canvas chosen for painting specific NASA human space flight and space exploration scenarios. The particular line of interest will be the blue line, the Exploration budget of about \$3 billion a year. In later years, 2024 to 2028 and beyond, the red lines will become important, as the fate of NASA's presence in low Earth orbit can take assorted paths. A reasonable scenario assumption (for starters) will apply to the black line items, assorted research, support and other standing functions, assumed to carry on steadily in support of whatever may come.

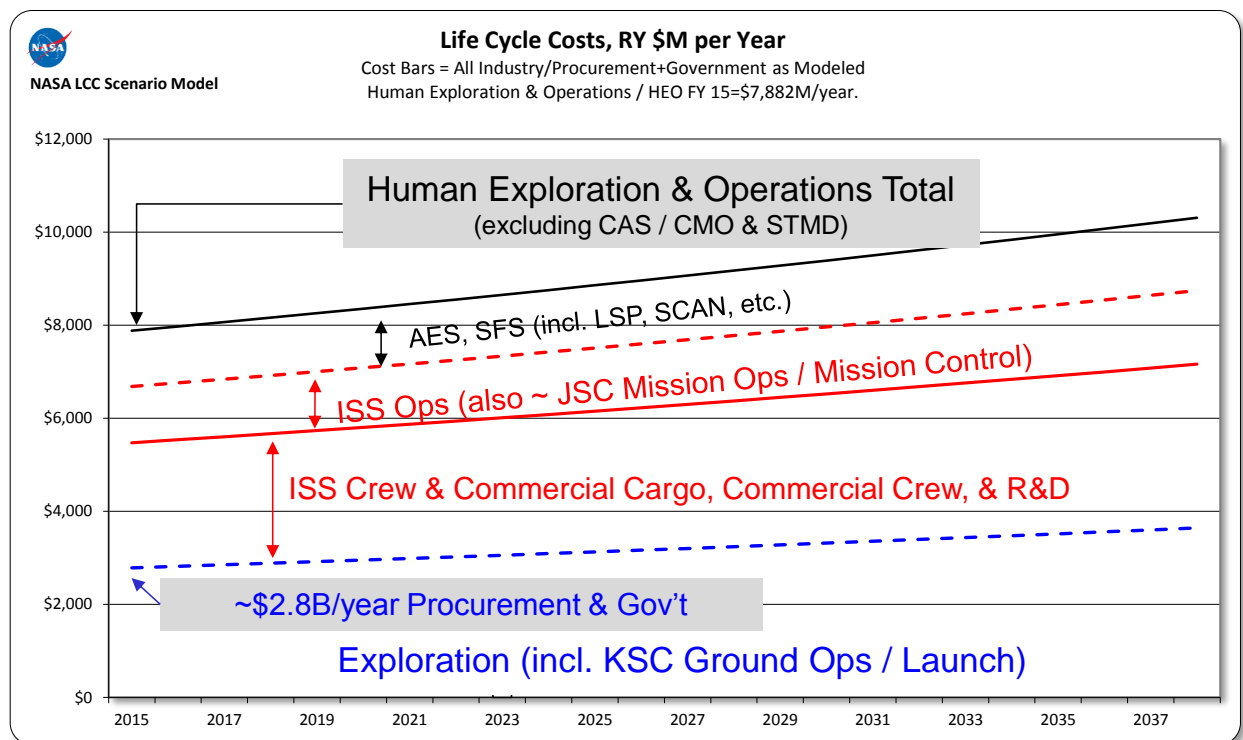


Figure 3. NASA Human Exploration & Operations Budgets. Note that this view excludes the Space Technology Mission Directorate (STMD), which is a separate directorate and fund line, apart from, and at the same level, as the NASA Human Exploration & Operations (HEO) funds.

V. Scenario Variable 1: NASA's Purchase Power

Changing only one variable a time helps to simplify the exploration of scenarios. NASA budgets and cost inflation, as with a person's salary and the cost of goods they buy, are actually two sides of one coin-purchasing power. The possible combination of possible budgets, and what outcomes these budgets might be able to afford, can seem overwhelming. Exploring the edges of a very big box can simplify things. One attempt at this follows –

“Implementable in the near-term with the buying power of current budgets and in the longer term with budgets commensurate with economic growth⁶”

This analysis will avoid the idea of “economic growth” for an equivalent but simpler approach. When the US gross domestic product shrinks, as during a recession, is NASA's budget cut? What relationship exists between the broader economy and the cost of very specific, and often unique, space systems? These economic complications are unnecessary to develop significant, useful observations from a simpler exploration of boundaries using purchase power scenarios. Three simple, but very useful, scenarios (Table 1) are-

- 1) **High Purchase Power Scenario** – Deviates from past trends, for the better. Here, the NASA budget goes up at whatever the inflation rate of space systems goods and services may be. As the NASA Inflation Index recommends 2.5%, this scenario can assume that starting immediately NASA starts getting 2.5% budget increases (on average) for the foreseeable future. The scenario is “optimistic” as this would mean NASA's future budget trend would be special, unlike most other federal agencies. **NASA's purchase power today in 2015 is the same as NASA's purchase power in 2025, or 2035.** Costs of any space systems today, inflated as time goes by, and today's budgets once increased, remain parallel to each other.
- 2) **Nominal Purchase Power Scenario** – Uses quantifiable data. The NASA budget goes up in the years ahead as it has in years past, an average of 1.175% a year, with cost inflation as indicated in an official NASA source, the NASA Inflation Index, which recommends 2.5%. **The nominal scenario continues to lose purchase power**, but is nominal by relying on data, having no subjectivity as to what may happen. Nominally, the future is like the past, as best we understood it.
- 3) **Low Purchase Power Scenario** – Deviates from past trends, for the worse. To simplify, inflation in space systems good and services may go up faster than 2.5% a year on average, while NASA still receives budget increase only on a par with past trends (1.175% a year). To carry the analysis to its end, the analysis here does not have to address why cost inflation may be more than 2.5%. (Reasons would include a shrinking space systems industrial base, possibly reduced defense spending affecting NASA's industrial base, demographics favoring the prior, etc.) Human Exploration & Operations purchase power in 2025 or 2035, would have the power of compound interest working against plans. **This means billions less a year in real purchase power terms by the 2030's, even as the real year budget seemed to go up every year.**

High Purchase Power Scenario: Average NASA budget increases 2016 forward are the same rate as the average cost inflation of the exploration & operations goods and services. (Both 2.5%).	Why “High”? A “what-if”, the NASA budget, increasing faster than supported by recent historical data.
Nominal Purchase Power Scenario: The NASA budget goes up yearly as it has in the past decade (1.175%). Cost inflation as officially recommended in the NASA Inflation Index (2.5%).	Why “Nominal”? Both budget and inflation rate increases supported by historical trend data or official NASA sources. No “what-if”.
Low Purchase Power Scenario: The cost inflation of goods and services required by NASA increases an additional 1% above the recommended NASA Inflation Index (3.5%). NASA yearly budget increases per recent historical data (1.175%).	Why “Low”? A “what-if”, cost inflation, increasing faster than supported by official NASA sources.

Table 1. Summary low, nominal and high NASA purchase power scenarios.

VI. Scenario Variable 2: Post-ISS Budget Availability for Other Exploration

As with the scenarios about purchase power, post-ISS budget availability scenarios can be simplified as optimistic, nominal, and pessimistic (as seen from the viewpoint of follow-up projects, not from the point of view of the ISS). The nominal scenario should be supported by available information, while being more linear, involving less subjectivity or “what if”. The optimistic scenario frees up more money, the pessimistic less, within some bounds still limited by knowledge about how budgets really behave. These three simpler, but still very useful, scenarios (are-

- 1) **High post-ISS Available Funding Scenario** – Frees up the maximum amount of funding post-ISS. Realism must still bound this scenario. For example, Mission Operations and Mission Control costs that are currently inside the ISS Operations budget would continue.
- 2) **Nominal post-ISS Available Funding Scenario** – Uses what information is available. NASA and its partners de-orbited the ISS in 2024 -or perhaps NASA upgraded the ISS, privatized it, or made it smaller. As well, NASA will be purchasing time on a private space station (or stations) as a (quote) “*anchor tenant*”⁷. This scenario only needs to plausibly bound budgets, not specific configurations, around the idea that some NASA low Earth orbit presence continues after 2024, indefinitely for planning purposes.
- 3) **Low post-ISS Available Funding Scenario** – Frees up the least amount of funding for other projects. This scenario is similar to the nominal scenario, but the end of the ISS is in 2028, and NASA’s continued presence in low Earth orbit requires more funds than if there were greater success in the development of private sector stations and their affordability.

High post-ISS Available Funding Scenario:	<p>Why “High”? A “what-if”, funding freed-up for other uses post-ISS, disregarding wholly the possibility of any continued NASA presence in LEO.</p> <p>Exception: ISS Operations as with Nominal (Mission Operations & Control).</p> <p>Sum=\$3,100M a year fully available</p>
Nominal post-ISS Available Funding Scenario:	<p>Why “Nominal”? An extrapolation consistent with NASA statements.</p> <p>ISS Operations: 1/3rd fully available, while other 2/3rds also available, but limited to use for (1) Mission Operations & Control for Exploration and (2) Mission Operations & Management of NASA personnel aboard private LEO stations. (\$400M a year fully available)</p> <p>ISS R&D: Reduced 50% (\$150M a year fully available)</p> <p>ISS Cargo & Crew: Reduced 50% (private stations, NASA as “anchor tenant”); Station owner handles in-their space operations and control. Reduction due to either less usage and/or bundling/block services consistent with “services”.</p> <p>Sum=\$1,750M a year fully available</p>
Low post-ISS Available Funding Scenario:	<p>Why “Low”? As with Nominal, but “what-if” ISS Cargo & Crew rides and related for a private space station in an anchor tenant role are reduced only 1/3rd from current levels. R&D remains at the same levels as today, but as NASA work occurring at private sector stations.</p> <p>Sum=\$1,500M a year fully available</p>

Table 2. Summary low, nominal and high post-ISS available funding scenarios. Values are in Fiscal Year 2015 dollars.

VII. Combining Scenario Variables

While the sums in the post-ISS scenarios may appear inviting, potentially the basis for a NASA lunar, Mars or other space exploration initiative beyond low Earth orbit, combining the low, nominal and high post-ISS scenarios with the low, nominal and high purchase power scenarios provides a starkly different perspective.

- 1) **The low and nominal post-ISS funding scenarios, combined with the nominal budget/inflation scenario, actually frees up zero (or negative) funding by the 2030's.** Purchase power loss will have eroded away any possible post-ISS funding, as a slow build-up of budget pressures over time across all NASA programs, perhaps manifesting as reduced productivity (outcomes and achievements), with the end of the ISS program consistent with the reduction in overall forward progress in exploration.
- 2) **The high post-ISS funding scenarios, combined with the nominal budget/inflation scenario, will free up less than \$10 billion in funding by the late 2030's – or less.** Purchase power loss will have eroded away a significant part of possible funding availability from the end of the ISS program, but not all, in this scenario with a high post-ISS funding availability. Alternately, given uncertainty in the industrial base, and assuming the low purchase power scenario, all this potential funding would have eroded away as well through purchase power losses.

Other combinations are possible, for example, the high post-ISS funding scenario and the high purchase power scenario, allowing many 10's of billions of dollars in funding to be applied to exploration, Mars, etc. in the 2030s. Combining NASA purchase power scenarios and the post-ISS scenarios sets the stage for understanding the range of budget possibilities in which potential NASA exploration concepts will (or will not) live. The greatest amount of purchase power and the greatest amount of funding freed up from the end of the ISS program would provide the greatest amount of funding available to proposed Exploration scenarios. The lowest amount of funding comes from combining the least purchase power with the least available post-ISS funding.

The scenarios explored ahead will often combine nominal scenarios for purchasing power and post-ISS available funding. The “budget” X “inflation” X “future of ISS” box having been explored for it's possible edges, the sheets ahead delve into individual possibilities, scenarios inside the prior scenarios, to see how well these fit (or not) inside the context that will be set by these edges.

The Life Cycle Cost model⁸ used to generate the diorama's ahead, its methodology and mechanics, is not the focus of this paper. The emphasis here is on the analytical results from such a model. As background, Figure 4 shows the models basic framework. The model is available on request from the author^{**}. A user guide accompanies the model taking the user through each step in the user interface, including examples.

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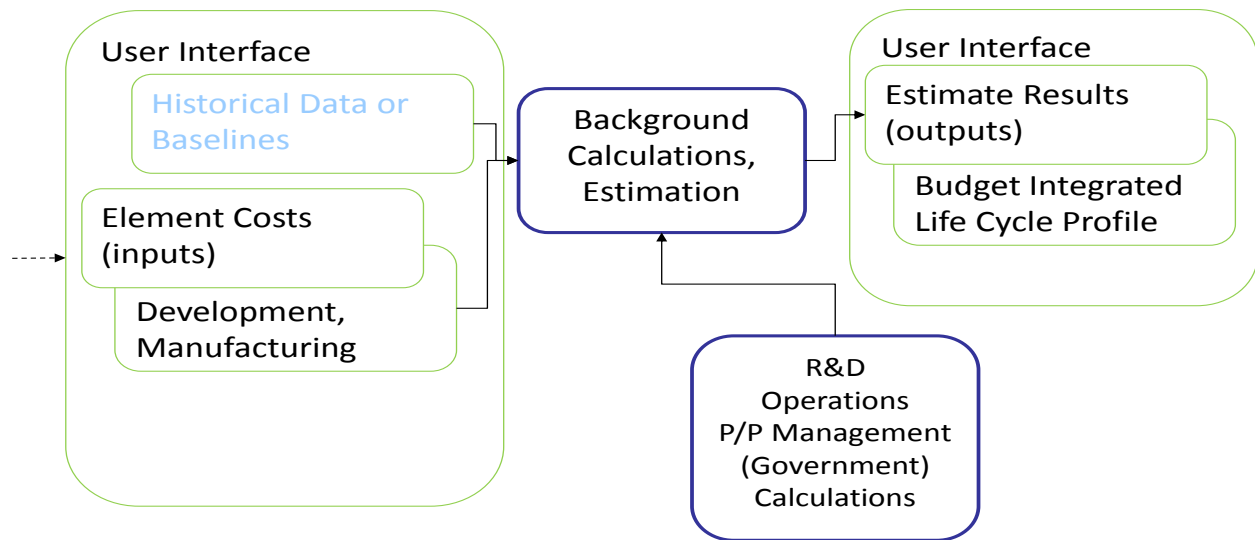


Figure 4. The framework of the Human Exploration & Operations Scenario Life Cycle Cost Model. Using a combination of historical data, subject matter expertise, guidance in the model, and internal calculations, a user generates a life cycle cost scenario for a set of elements inside a NASA budget/inflation scenario of their choosing.

Hard cost data from on-going and past projects being so critical to understanding future costs, the LCC model has abundant data, from older to recent, from launch systems to spacecraft, from cost-plus to commercial, and from crewed to non-crewed (cargo) data points. The data stretches from non-recurring (development) to recurring (manufacture and operations). Users uninterested in the LCC model are free to explore and use the data or the data's sources, documented throughout. Data as facts-on-the-ground are critical to analyzing the feasibility of future scenarios within the edges set by any "budget" X "inflation" X "future NASA LEO presence" context. By way of example, Figure 5 summarizes some of the LCC models spacecraft data for development as well as recurring manufacturing costs to NASA (industry costs to NASA, exclusive of other costs such as NASA / government management costs, etc.)

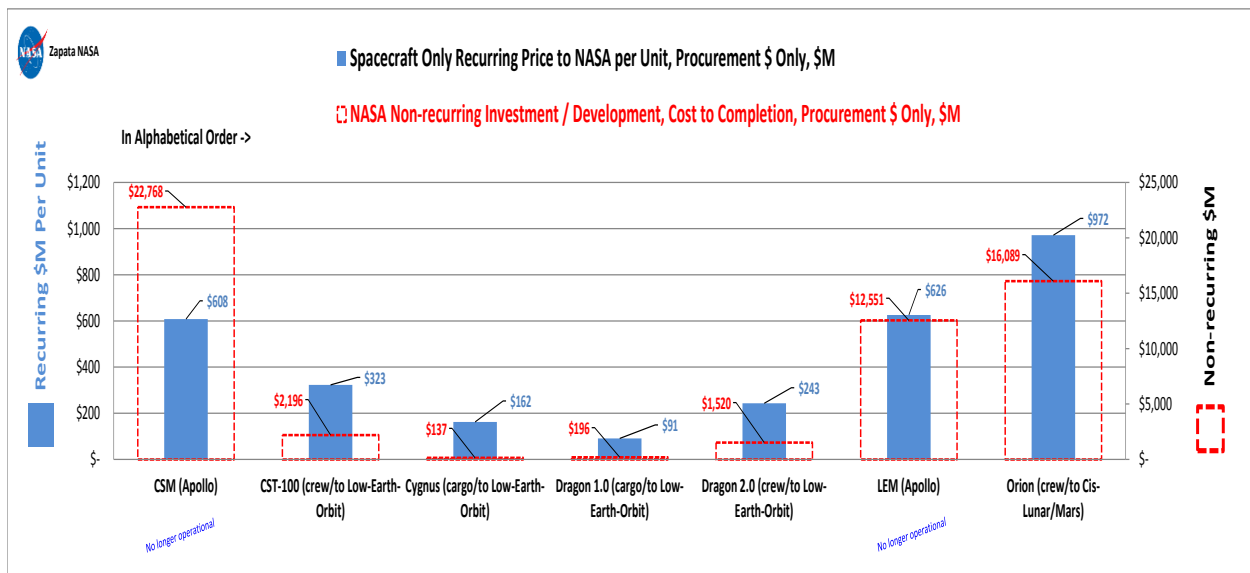


Figure 5. Summary spacecraft data from the LCC model. Non-recurring development costs (red/dashed), units on the right-axis, and recurring manufacturing unit costs (blue/solid), units on the left axis.

VIII. Scenario Sheets

Each scenario sheet ahead will begin with a general description, a storyline of sorts. Is this a scenario where NASA returns to the Moon, or Mars, where the SLS is included, with spacecraft X or spacecraft Y? What is the basic premise of this future in the multi-verse of possible futures? What guidance or target was used in phasing, scheduling, the cost estimates over time? Particularly, is there an attempt to stay below some fixed budget line?

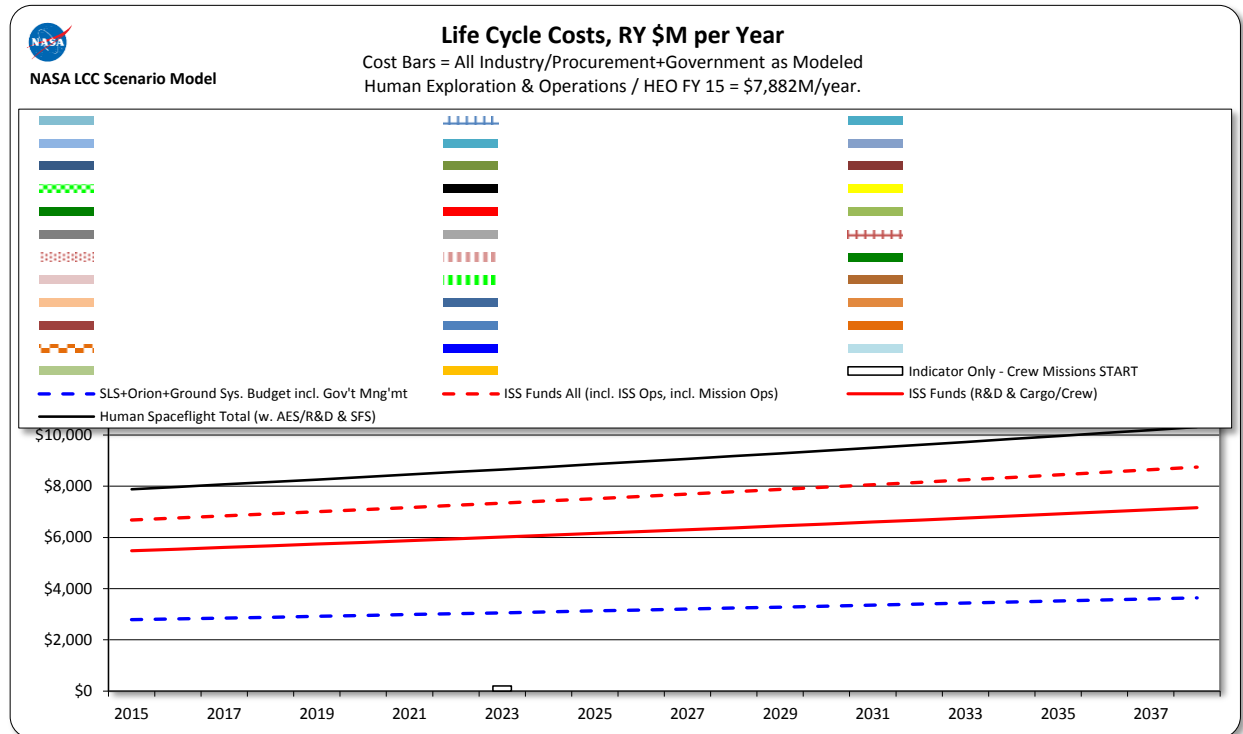


Figure 6. Title of Scenario. A description of each scenario. Blanks in the legend are un-used or inapplicable elements in the specific scenario.

Settings: Settings will list especially important variables, some being inputs, others outputs, including:

- 1) IN- Budget/Inflation: Low, Nominal or High Purchase Power Scenario
- 2) IN- Post-ISS Scenario: Low, Nominal or High Post-ISS Funding Scenario
- 3) IN- Major Elements: List
- 4) IN- Frequency of missions, every X years: no.
- 5) OUT- Number of any launches per year, average: no.
- 6) OUT- Number of tanker launches, per mission: no., as applies
- 7) OUT- Propellant (LO/LH) \$/kg: no., as applies

Observations:

Observations will address how well the scenario adds up against the chosen context, as well as issues the life cycle cost graph may not make readily apparent. In addition, note-

- **Flows of Funds, not Elements:** Funds for efforts must precede a mission or other milestone completion by some time. There may seem to be an odd sequence or flow of elements, fine when seen as funds flowing.
- **Costs vs. Prices:** An estimated price from a partner is the cost to NASA reflected in these budget graphs. The actual costs incurred by the partner are not relevant here, as the interest is in what NASA would have to budget; e.g. a procurement cost for goods or services atop which will rest still other related costs shown (government program and project management, or ground operations testing, or mission operations, for example).
- **Overages, Cost Bars Exceeding Blue Lines, Red Lines, etc.:** In any scenarios, for example content \$ bars exceeding the dashed blue line, should be interpreted as challenges for the scenario, in proportion to the overage, and usually meaning that either schedule or mission/flight rate capability, or both, will be less than inputted for the scenario. (The project cannot actually spend funds that are not there).

IX. The Interim Scenario – SLS (& ICPS), Orion - Nominal

The Baseline Scenario is merely a starting point, an extrapolation of the SLS and Orion in the 70t payload configuration. The 70t configuration includes an Interim Cryogenic Propulsion Stage (ICPS), with this upper stage as part of the 70t payload capacity to LEO (and within the SLS costs). In the operational years, launches occur twice a year.

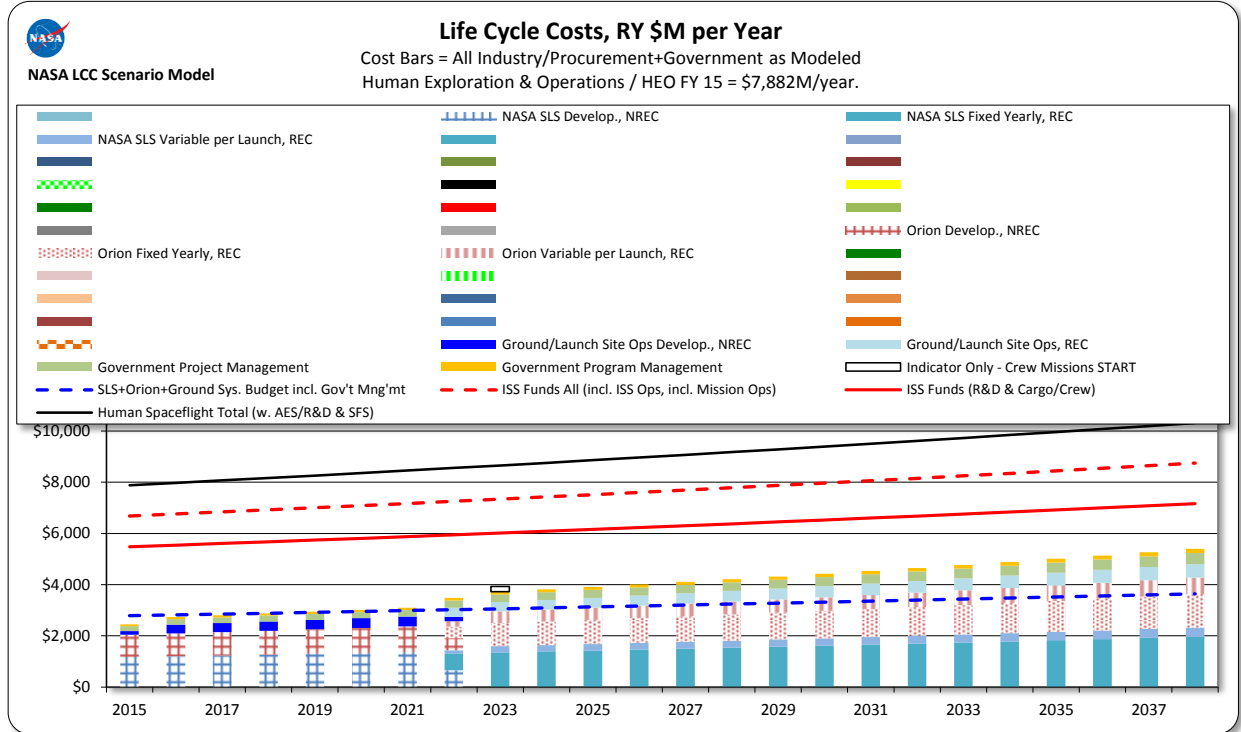


Figure 7. The Interim Scenario LCC results, with the ICPS. The SLS/Orion in the 70t configuration (with ICPS upper stage), as-if carried out indefinitely, launching twice a year after development is completed.

Settings:

- 1) IN- Budget/Inflation: **Nominal** Purchase Power Scenario (Budget 1.175%/year, Inflation 2.5%/year)
- 2) IN- Post-ISS Scenario: **Nominal** Post-ISS Funding Scenario (\$1,750M/year available post-2024)
- 3) IN- Major Elements: SLS (with ICPS), Orion
- 4) IN- Frequency of missions, every X years: **0.5**
- 5) OUT- Number of any launches per year, average: **2.0**
- 6) OUT- Number of tanker launches, per mission: **n/a**
- 7) OUT- Propellant (LO/LH) \$/kg: **n/a**

Observations:

In practice, after development completes in 2021, operational funding (above the blue line) capable of a steady two flights a year must await at least 2025 and the nominal post-ISS funding availability, not 2023. No other funding is available in extending this interim scenario for any other purposes than the twice a year launch rate and the post-ISS LEO presence, which persists in this nominal post-ISS scenario. Although the SLS operational costs are an estimate, derived from an analysis of the Space Shuttles fixed and variable costs⁹, and therefore uncertain, the estimate shown is the “low” based on such an extrapolation. This indicates challenges ahead for any interim SLS, nominal post-ISS scenario if NASA is to divert funding circa 2024-2028 to the development of new space exploration elements (there is no funding left over).

X. The Baseline Scenario – SLS (& EUS), Orion – Nominal Purchase Power

Achieving the intended, higher payload capability of the SLS includes plans for a larger upper stage, an Earth Departure Stage (EDS) of a scale consistent with the departure stages required in NASA Mars exploration scenarios^{10,11}. This Exploration Upper Stage (EUS) better completes the LCC picture in SLS/Orion scenarios.

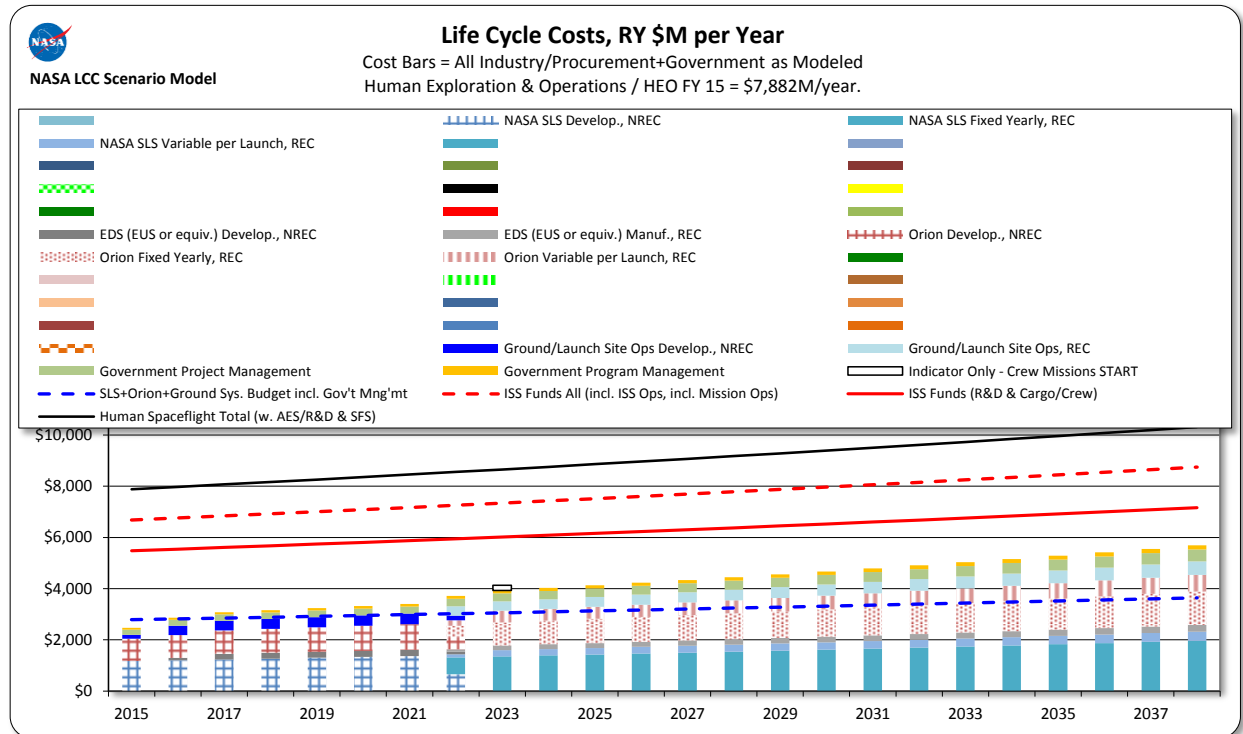


Figure 8. The Baseline Scenario LCC results, with the EUS. *The SLS/Orion in the larger payload configuration (with EUS upper stage), launching twice a year after development is completed.*

Settings:

- 1) IN- Budget/Inflation: **Nominal** Purchase Power Scenario (Budget 1.175%/year, Inflation 2.5%/year)
- 2) IN- Post-ISS Scenario: **Nominal** Post-ISS Funding Scenario (\$1,750M/year available post-2024)
- 3) IN- Major Elements: SLS/EUS, Orion
- 4) IN- Frequency of missions, every X years: **0.5**
- 5) OUT- Number of any launches per year, average: 2.0
- 6) OUT- Number of tanker launches, per mission: n/a
- 7) OUT- Propellant (LO/LH) \$/kg: n/a

Observations:

Similar to the prior ICPS scenario, made slightly worse, as the EUS is more expensive than the ICPS in exchange for the increased payload capability per launch and the usefulness of this scale upper stage for space exploration scenarios, for leaving Earth orbit.

XI. The Baseline Scenario – SLS (& EUS), Orion – High Purchase Power

Purchase power can affect any scenario significantly, the power of compound interest over time. Here that power of compounding over time benefits the scenario. In one perspective, the NASA budget only goes up an extra 1.325% a year over recent historical trends. In another perspective, the same number means NASA's budget would be going up at over twice the recent historical trend of 1.175% per year.

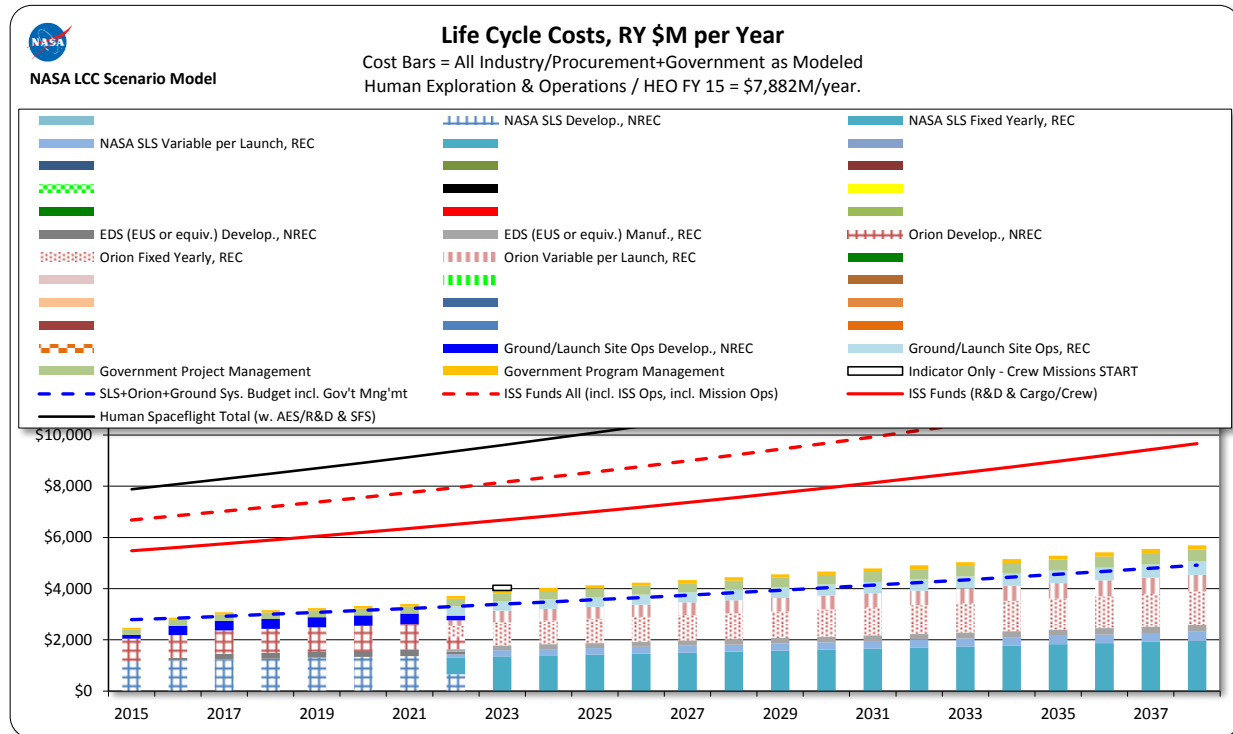


Figure 9. The Baseline Scenario LCC results, with EUS. The SLS/Orion in the larger payload configuration (with EUS, the larger upper stage), launching twice a year after development is completed.

Settings:

- 1) IN- Budget/Inflation: **High** Purchase Power Scenario (Budget 2.5%/year, Inflation 2.5%/year)
- 2) IN- Post-ISS Scenario: **Nominal** Post-ISS Funding Scenario (\$1,750M/year available post-2024)
- 3) IN- Major Elements: SLS/EUS, Orion
- 4) IN- Frequency of missions, every X years: **0.5**
- 5) OUT- Number of any launches per year, average: 2.0
- 6) OUT- Number of tanker launches, per mission: n/a
- 7) OUT- Propellant (LO/LH) \$/kg: n/a

Observations:

Due to increasing the NASA budget at a rate matching cost inflation, the scenario that previously appeared challenged now looks more plausible. Given the nominal post-ISS funding scenario, according to this estimate about half of the funding freed up post-2024 would be required to support the 2 SLS/Orion launches a year, with the other half (under \$1B a year) available for the future space exploration elements. Significant challenges remain in this scenario – principally the ability to balance the SLS/Orion flight rate, requiring post-ISS funds, and the need to develop payloads for these flights, those future exploration elements. With under \$1B a year freed up post-ISS for new space exploration elements, and the remainder for even one SLS/Orion flight a year, it would be 10 years before a cumulative \$10B (in 2015 \$) was made available to develop and make future space exploration elements.

XII. The Baseline Scenario – SLS (& EUS), Orion – Low Purchase Power

Purchase power can affect any scenario significantly, the power of compound interest over time. Here that power works against the scenario. While it may seem an unlikely worse case, cost inflation at 3.5%, it's worth remembering this value is for unique aerospace goods and services, space systems in low volumes even relative to historical standards (the Space Shuttle flight rate averaged 5 a year). Industrial base challenges^{12,13} and the uncertainty over the inflation rate¹⁴ for unique space systems would support such a scenario actually being less than worse case.

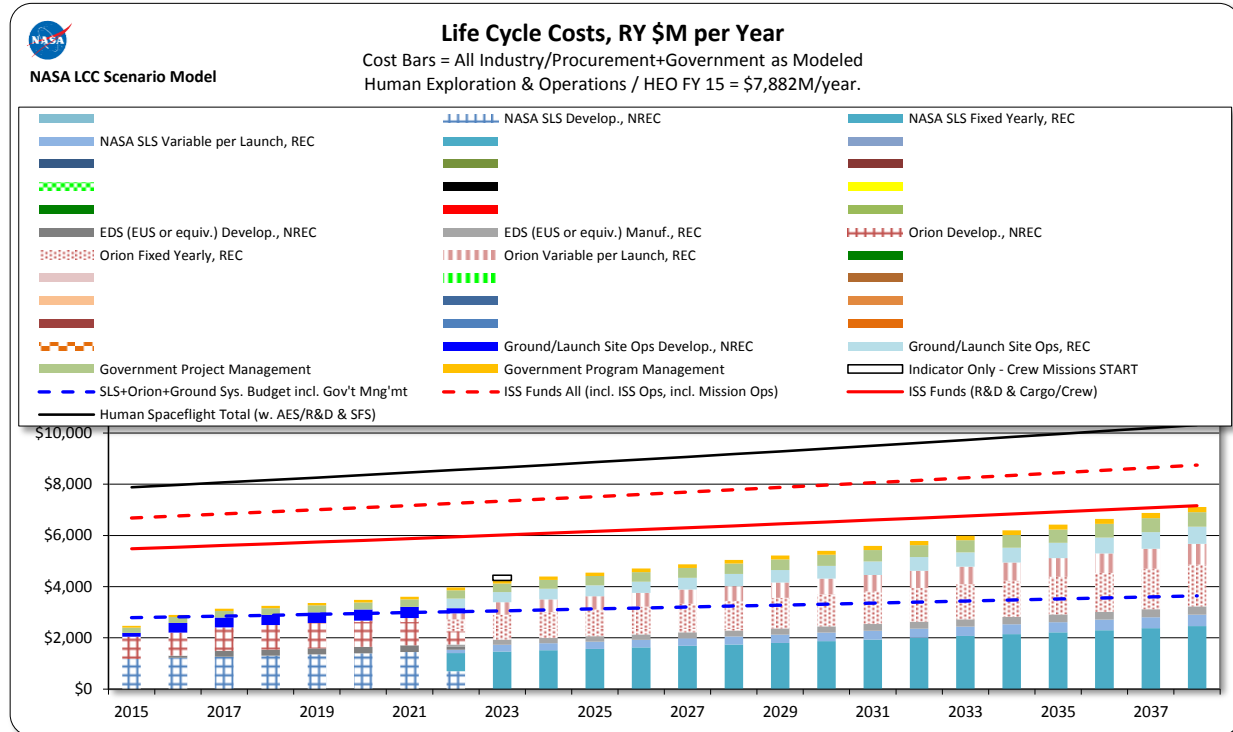


Figure 10. The Baseline Scenario LCC results, with an EUS. The SLS/Orion in the larger payload configuration (with EUS upper stage), launching twice a year after development is completed.

Settings:

- 1) IN- Budget/Inflation: **Low** Purchase Power Scenario (Budget 1.175%/year, Inflation 3.5%/year)
- 2) IN- Post-ISS Scenario: **Nominal** Post-ISS Funding Scenario (\$1,750M/year available post-2024)
- 3) IN- Major Elements: SLS/EUS, Orion
- 4) IN- Frequency of missions, every X years: **1.0**
- 5) OUT- Number of any launches per year, average: **2.0**
- 6) OUT- Number of tanker launches, per mission: **n/a**
- 7) OUT- Propellant (LO/LH) \$/kg: **n/a**

Observations:

Besides being a low purchase power scenario, the flight rate for the SLS/Orion, versus previous scenarios, is now only one flight/year, not two. (There is insufficient funding for 2 flights/year given the nominal post-ISS funding availability scenario, \$1,750M in 2015 \$, by way of example being \$2,500M in 2038). This scenario closes at this lower flight rate, leaving some funding in the 2020's for the development of new space exploration elements, but the loss of purchase power eventually erodes this wedge to zero by 2038.

In addition, the usual issues of violating the blue-line up through 2024 would indicate this scenario faces nearer term challenges that could delay the EUS and use of the SLS/Orion before 2025.

Further, separating guidance on cost inflation from an understanding of actual cost inflation would improve the understanding of such scenarios. In NASA, as in the Department of Defense, this separation remains unclear.

"The FMR's guidance is unclear. It states that a DOD budget submission must "reflect most likely or expected full costs." The next paragraph, however, mandates the use of the OUSD(C)-provided rates."¹³

XIII. Alternate Scenario 1 – Lunar Exploration via Commercial & In-space Refueling

A non-linear scenario breaking from the prior baseline could begin with an attempt to back into an architecture given the nominal budget/inflation (and ongoing loss of purchase power) alongside the nominal post-ISS scenario for funding availability. One such class of scenarios would use refueling in-space, an Earth orbit rendezvous / lunar orbit rendezvous architecture, Falcon Heavy, Delta IV Heavy and modified commercial crew spacecraft (the modification being to upgrade to lunar and 21-day mission requirements).

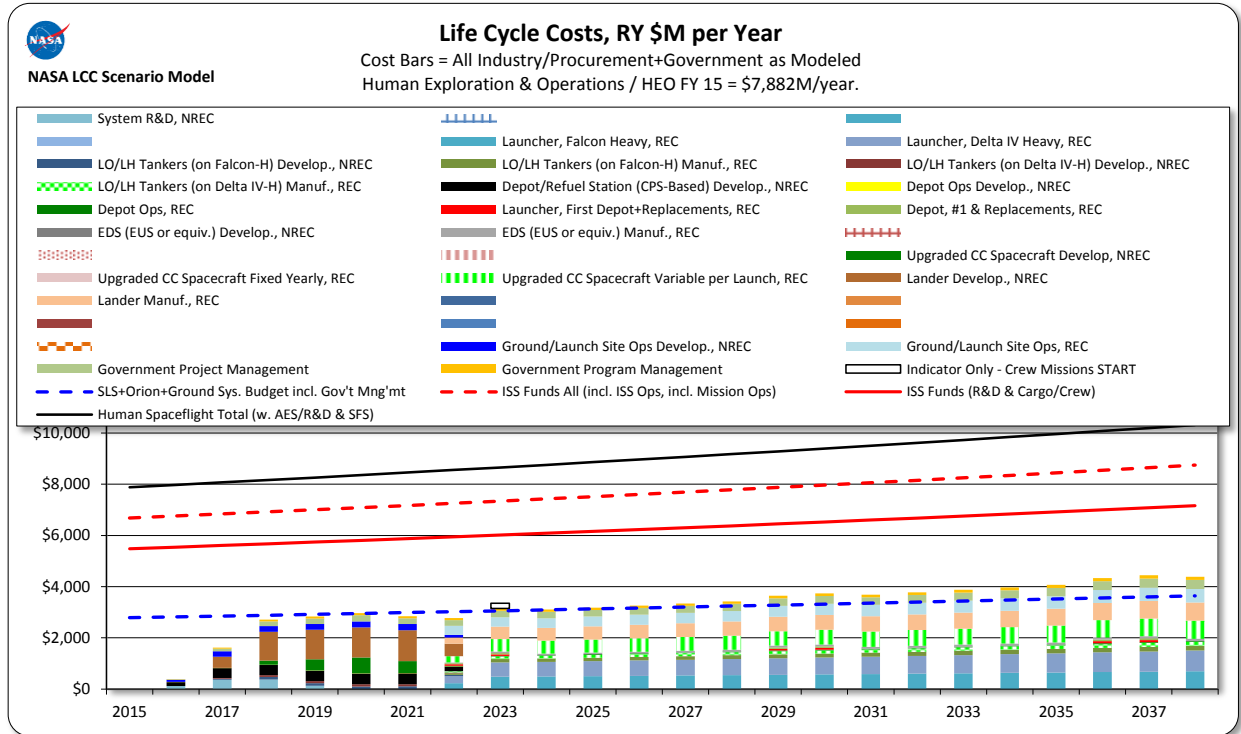


Figure 11. Alternate Scenario 1 – Lunar Exploration via Commercial Launchers and In-space Refueling Infrastructure. More elements are required, but with redundant providers, just as in current ISS cargo/crew ops.

Settings:

- 1) IN- Budget/Inflation: **Nominal** Purchase Power Scenario (Budget 1.175%/year, Inflation 2.5%/year)
- 2) IN- Post-ISS Scenario: **Nominal** Post-ISS Funding Scenario (\$1,750M/year available post-2024)
- 3) IN- Major Elements: Refueling stage (with a lifetime of 7 years in space), commercial propellant tankers
- 4) IN- Frequency of missions, every X years: **1.0**
- 5) OUT- Number of any launches per year, average: **6.0**
- 6) OUT- Number of tanker launches, per mission: **4.0**
- 7) OUT- Propellant (LO/LH) \$/kg: **\$5,000/kg**

Observations:

The scenario assumes the cancellation of the SLS/Orion programs, freeing up that funding into a major re-direction for NASA. The first mission to the Moon occurs in 2023, with the need to collaborate with industry on tankers (akin to upper stages), an in-space propellant depot where the commercial tankers deposit propellant, commercial space operations, modifications to commercial crew spacecraft for lunar trips, and a new lunar lander.

This scenario could also segue away from what would become repetitive trips to the Moon by 2030, morphing in assorted directions dependent on learning, the establishment of in-space infrastructure and the degree to which delivered propellant costs could go lower.

Conservative values have been used for launcher prices to NASA (which are above any advertised rates), as well as for most items. For example, the assumption is made a modification to commercial crew spacecraft would entail as much development cost again as the entire development of these initially (also see Figure 5) for the ISS mission-an extremely conservative estimate.

XIV. Alternate Scenario 1 – Same as Prior, but Falcon Heavy Prices across Redundant Providers

As these life cycle views are funds flows for NASA acquiring certain outcomes alongside contractors and/or partners, it's possible to keep the redundant provider proviso in these commercial launcher/tanker scenarios while assuming two such providers at prices nearer the possible low-end. The funds flow looks no different from having one provider, but the scenario costs are lower, driven by the achievement of the propellant costs, a sum of the tankers and their launchers, losses, operational costs for the refueling node, and the replacement of these over time.

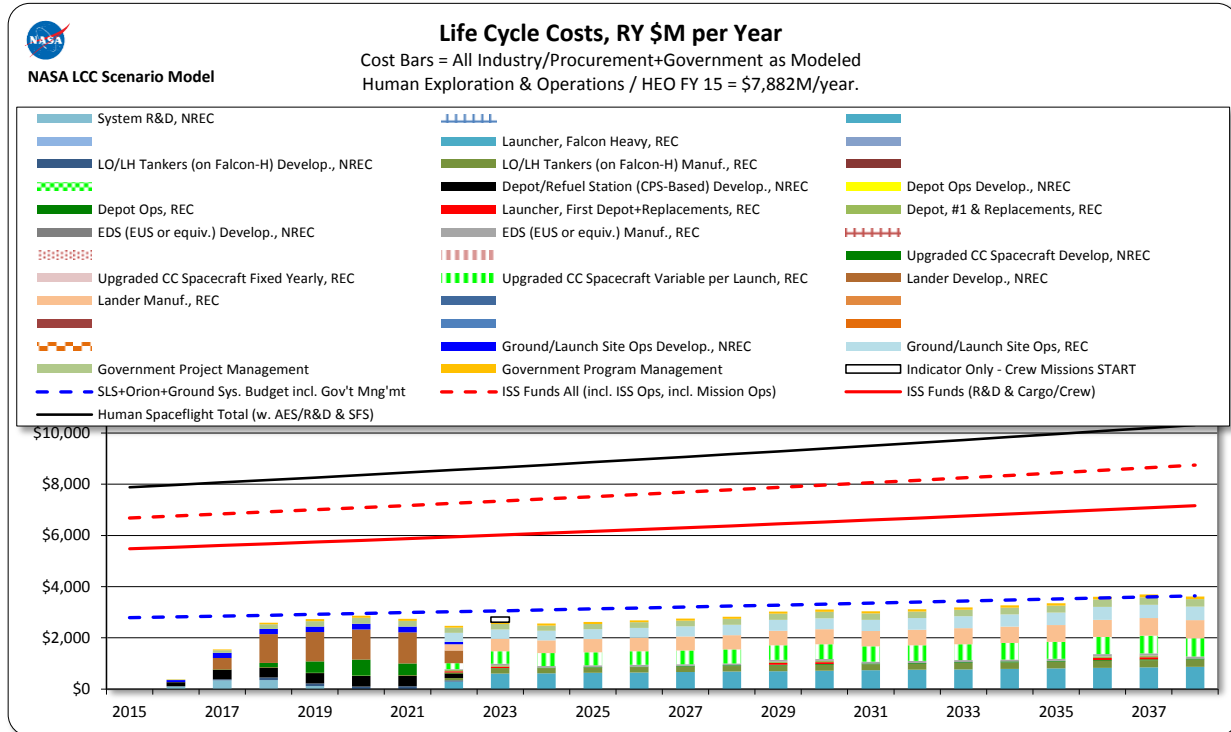


Figure 12. Alternate Scenario 1 – Lunar Exploration via Commercial Launchers and In-space Refueling Infrastructure. Assuming prices per kg at the lower end of possible costs, and two providers, leaves ample margin.

Settings:

- 1) IN- Budget/Inflation: **Nominal** Purchase Power Scenario (Budget 1.175%/year, Inflation 2.5%/year)
- 2) IN- Post-ISS Scenario: **Nominal** Post-ISS Funding Scenario (\$1,750M/year available post-2024)
- 3) IN- Major Elements: Refueling stage (with a lifetime of 7 years in space), commercial propellant tankers
- 4) IN- Frequency of missions, every X years: **1.0 (meaning 1 mission every 12 months)**
- 5) OUT- Number of any launches per year, average: **5.0**
- 6) OUT- Number of tanker launches, per mission: **3.0**
- 7) OUT- Propellant (LO/LH) \$/kg: **\$3,000/kg**

Observations:

Events such as a new partnership (with NASA again using the Commercial Orbital Transportation Services / COTS development and service acquisition model) or current events such as the evolution of the United Launch Alliance Vulcan¹⁵ launchers would be consistent with this scenario. The scenario is missing development of the second providers launcher but this would not significantly affect the LCC (and would barely show) if close to repeating the experience of the ISS cargo program.

More significantly, this scenario opens the door to viewing the blue-line as a funding limit for transportation *and* propellant for the future elements to come in exploration. Given the nominal post-ISS funding scenario, this case shows ample margin (it has used none of the \$1,750M a year freed up post-ISS) to segue into an assortment of directions after 2024-2028, increasing the mission tempo, or developing and placing new elements of exploration infrastructure on the Moon. This could segue in turn towards Mars (discussed further ahead).

XV. Alternate Scenario 1 – Same as Prior, But Semi-Reusable Launch

Semi-reusable launch, for example, the reusable Falcon 9 first stage in development¹⁶, or as proposed with the recovery of propulsion modules¹⁷ from future Vulcan launchers, offers a path to even lower launch costs, affecting the acquisition price of propellant delivered to an in-space refueling node. Again, provided this opens a path to more than just one provider at the prices supported by extrapolating current launch prices to NASA, alongside the in-space refueling costs (the refueling point in space, it's operation, etc.) *tempo can now be increased to two a year.*

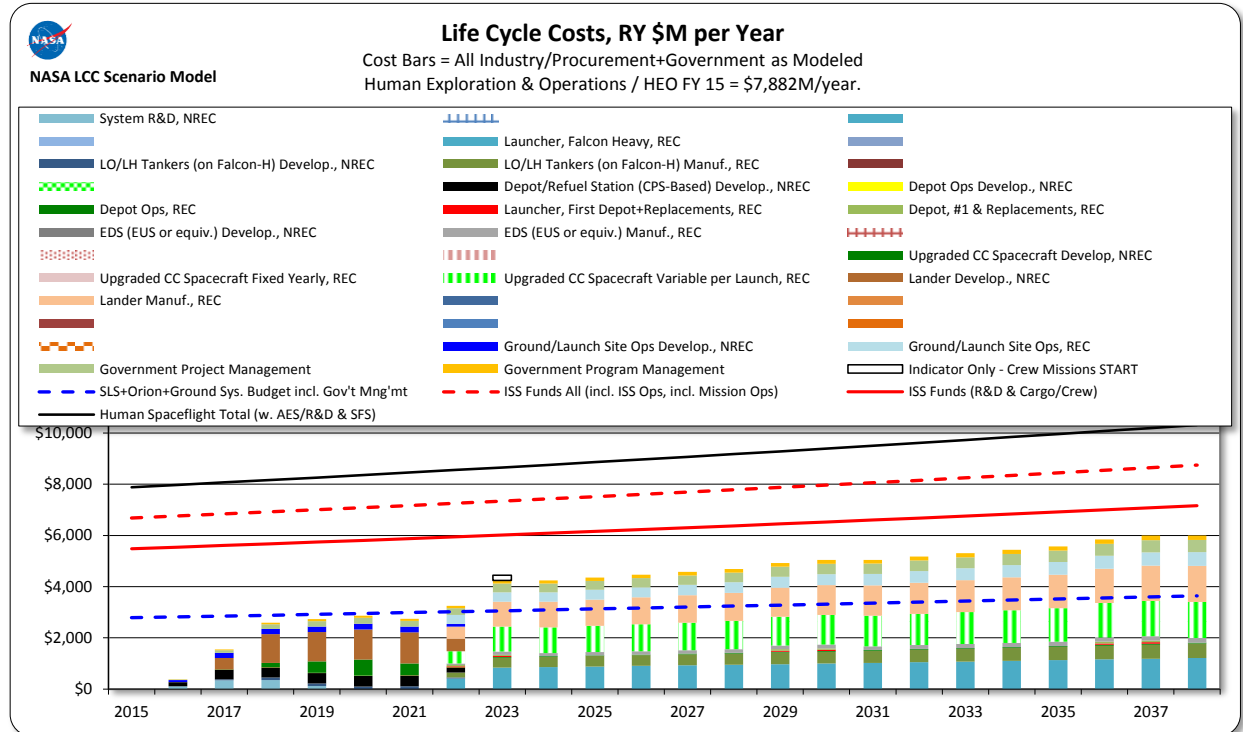


Figure 13. Alternate Scenario 1 – Lunar Exploration via Commercial Launchers and In-space Refueling Infrastructure. The tempo increases over the prior, employing lower price semi-reusable launch services.

Settings:

- 1) IN- Budget/Inflation: **Nominal** Purchase Power Scenario (Budget 1.175%/year, Inflation 2.5%/year)
- 2) IN- Post-ISS Scenario: **Nominal** Post-ISS Funding Scenario (\$1,750M/year available post-2024)
- 3) IN- Major Elements: Refueling stage (with a lifetime of 7 years in space), commercial propellant tankers
- 4) IN- Frequency of missions, every X years: **0.5 (meaning 1 mission every 6 months)**
- 5) OUT- Number of any launches per year, average: 10
- 6) OUT- Number of tanker launches, per mission: 3.0
- 7) OUT- Propellant (LO/LH) \$/kg: \$2,400/kg

Observations:

Uncertainties here begin with the interaction of lowering a price by recovering a stage versus losing some performance, and hence propellant delivery capability, or increasing the total launches over a time, arising industrial, range and other capacity issues. Nonetheless, the scenario is intriguing in its ability to remain within the nominal budget/inflation assumption (NASA continues losing purchase power) and the nominal post-ISS funding availability scenario.

This scenario can develop other elements initially as well, given the margin at the start of this scenario, even with generous consideration for the crewed lunar lander development, enough to support two lunar lander partner/providers in a commercial acquisition model. The lower launch prices, for simple cargo (propellant), in a block or “anchor tenancy” mode, again opens the door to either lunar exploration, infrastructure, or a combination that later helps either the economics or performance for Mars exploration.

XVI. Alternate Scenario 2 – In-Space Refueling and Asteroid Missions

Figure 14 shows a non-linear scenario that shifts gears to explore asteroids, again using refueling. As the timing of asteroid missions is rather complex, dependent on locating scientifically valuable and physically reachable targets, reachable being constrained by any chosen architectures capabilities, the scenario mostly helps reflect on other scenarios, such as Mars, that may have similar performance requirements of launchers and their Earth departure stages.

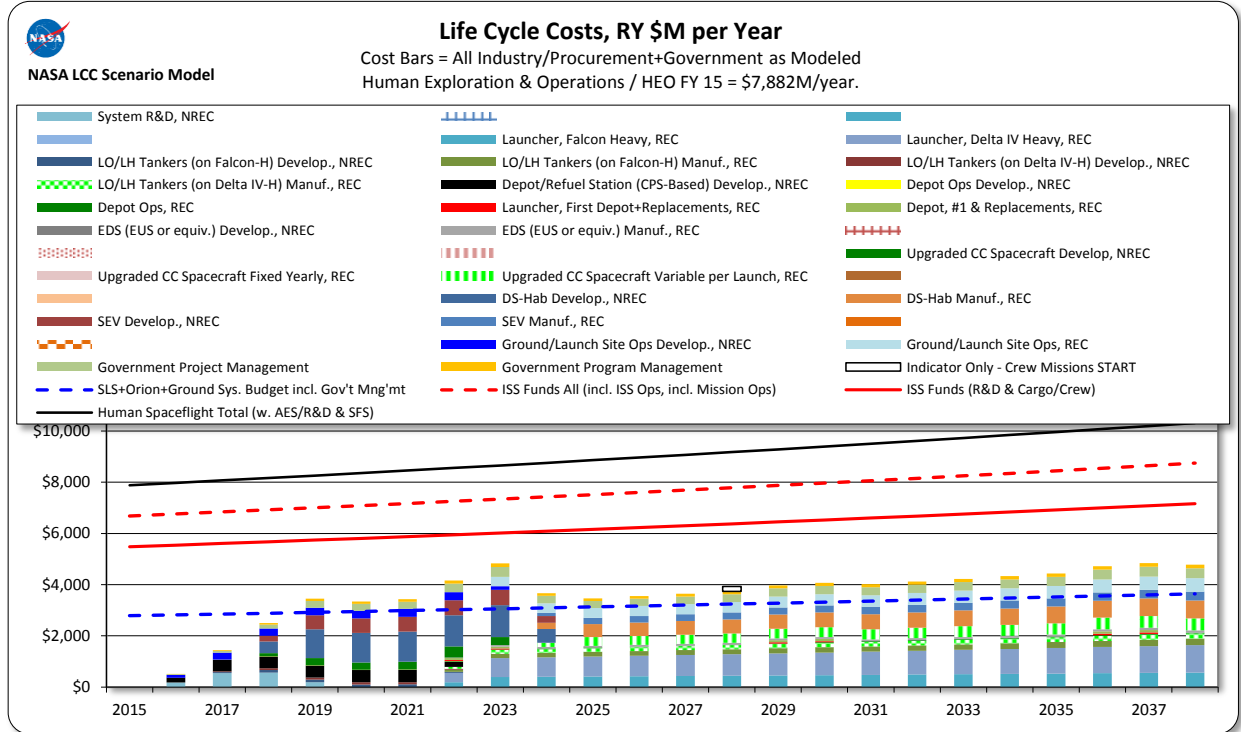


Figure 14. Alternate Scenario 2 – In-space Refueling, Commercial Launchers and Asteroids. *More elements are required (a habitat, an in-space exploration vehicle, etc.) as well as the larger Earth Departure Stage.*

Settings:

- 1) IN- Budget/Inflation: **Nominal** Purchase Power Scenario (Budget 1.175%/year, Inflation 2.5%/year)
- 2) IN- Post-ISS Scenario: **Nominal** Post-ISS Funding Scenario (\$1,750M/year available post-2024)
- 3) IN- Major Elements: Refueling stage (with a lifetime of 7 years in space), commercial propellant tankers
- 4) IN- Frequency of missions, every X years: **1.5**
- 5) OUT- Number of any launches per year, average: **6.0**
- 6) OUT- Number of tanker launches, per mission: **6.0**
- 7) OUT- Propellant (LO/LH) \$/kg: **\$4,700/kg**

Observations:

The example for this scenario above includes redundant launch providers, just as in current ISS cargo/crew ops. While appearing similar to an SLS/Orion scenario that would explore an asteroid in the 2020's¹⁸, similar to the 2028 date in this scenario, a key difference is completing the development of many exploration elements that are key to many an exploration scenario, before any consideration of the fate of the ISS, before the 2024/2028 timeframe.

As well, one element developed in this scenario (but necessary at only about half scale in the lunar scenarios) would be an Earth Departure Stage. This would perform a function just as in SLS/Orion scenarios and the EUS (but at about twice scale). This departure stages development is common, perhaps with the same provider, with much of the refueling station's design, to maintain the manufacturing capability for refueling station replacements, when required according to their life limits. Figure 18 and Figure 19 contrast the scales involved in these Earth departure stages, where smaller stages (lunar scale) are mated in-space to perform the same missions (asteroids, Mars) as larger scale stages.

XVII. “What-if” Scenario – SLS/EUS, Orion and a Mars “What-if 13/2.5”

Using the concept that a “what-if” life cycle view merely needs to see “that which remains” of budget, after defining those elements better understood now, a life cycle cost view of a Mars DRA 5.0 type scenario is possible. Assuming a \$13.5 billion development for Mars mission elements excluding transportation to LEO (SLS, Orion), and \$2.5 billion per Mars mission element set after, again excluding transportation, yields the life cycle costs in Figure 15.

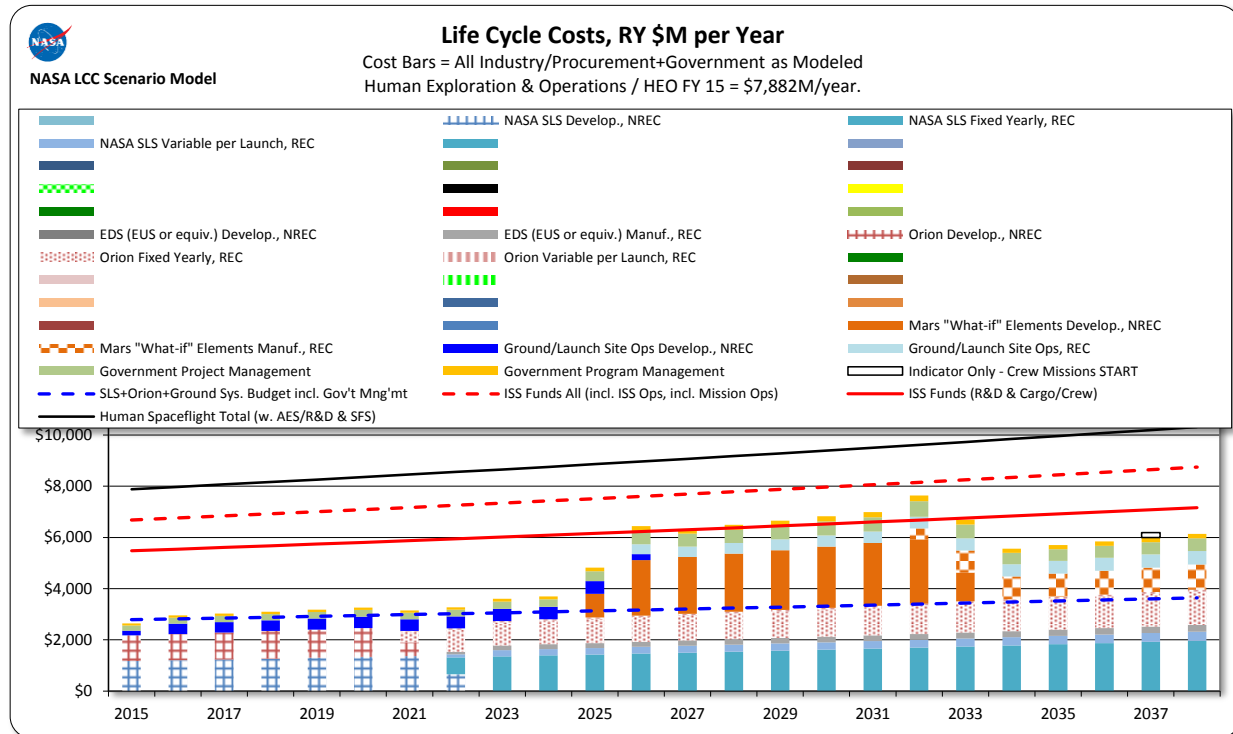


Figure 15. “What-if” Scenario – SLS, Orion and Mars. The “what-if” development and recurring costs of Mars elements such as habitat, logistics modules, landers (descent/ascent), etc.

Settings:

- 1) IN- Budget/Inflation: **Nominal** Purchase Power Scenario (Budget 1.175%/year, Inflation 2.5%/year)
- 2) IN- Post-ISS Scenario: **Nominal** Post-ISS Funding Scenario (\$1,750M/year available post-2024)
- 3) IN- Major Elements: SLS/EUS, Orion, Mars Elements as “what-if” (defined only as \$ develop, make, etc.)
- 4) IN- Frequency of missions, every X years: **4.5**
- 5) OUT- Number of any launches per year, average: **2**
- 6) OUT- Number of tanker launches, per mission: **n/a**
- 7) OUT- Propellant (LO/LH) \$/kg: **n/a**

Observations:

In its nominal mode, this “what-if” fails, using more funding than is available post-ISS, especially in 2025 to 2034. However, in the post-ISS scenario of maximum funds availability, the scenario does nearly close. Alternately, to fit a nominal post-ISS funds availability scenario, the “what-if” development phase would stretch further. Given the desire to have the first Mars mission within 20 years though, the required phasing of the “what-if” values of 13/2.5 are consistent.

The frequency of missions is about twice a decade. It is undefined what the SLS/Orion system are used for during the years 2022 (post development completion) through 2032 (the start of a Mars campaign), excepting that the development of Mars elements (habitat, etc.) would naturally include some integrated test flights with the SLS – the test elements are the SLS payloads. An advanced booster for the SLS as proposed¹⁹ would be an additional cost, perhaps using funds from the post-ISS \$13.5 billion for development (a large uncertainty).

XVIII. “What-if” Scenario – In-Space Refueling and a Mars “What-if - 13/2.5”

Again, a non-linear scenario breaking from the prior Mars-via-SLS could begin with an attempt to back into an architecture given the nominal budget/inflation (and ongoing loss of purchase power) alongside the nominal post-ISS scenario for funding availability. One such class of scenarios would use refueling in-space, Falcon Heavy and Delta IV Heavy, and modified commercial crew spacecraft (the modification being to upgrade to Orion equivalent mission requirements). As previously set, the Mars in-space element costs and the mission frequency are the same.

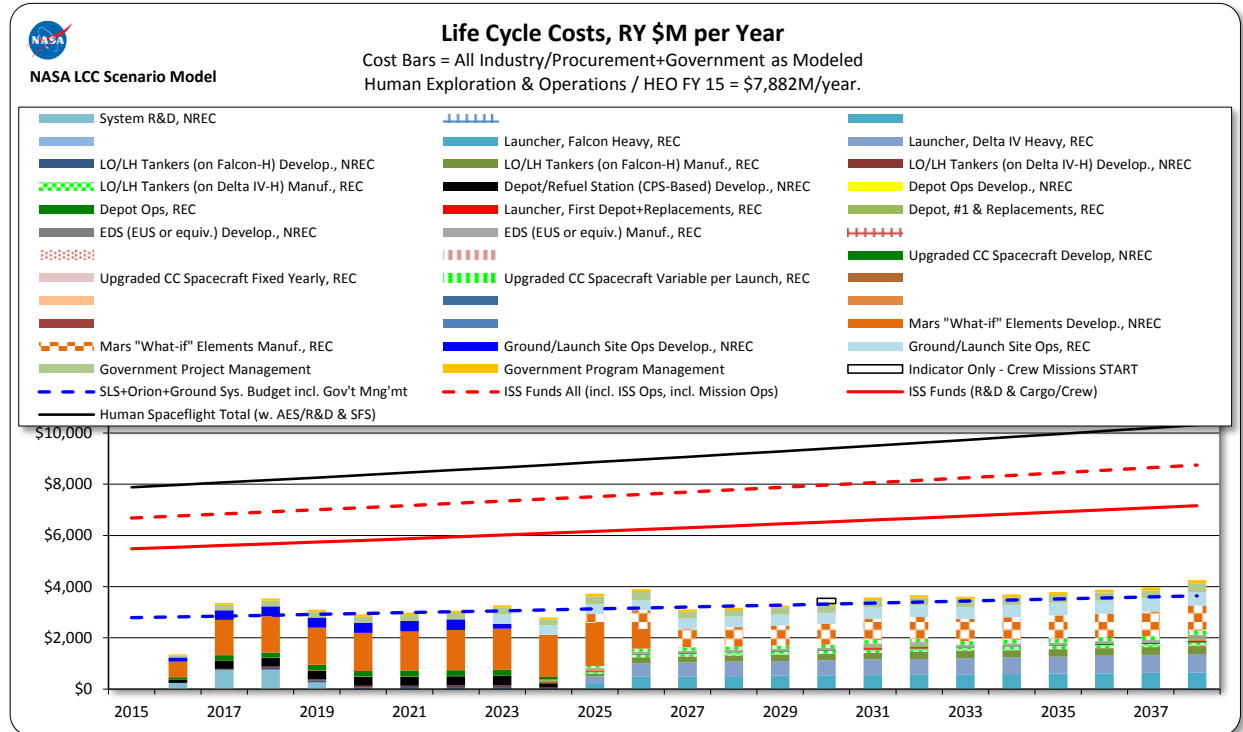


Figure 16. “What-if” Scenario – Tankers, Refueling of Earth Departure Stages and Commercial Launch.
Providers deliver propellant to a LEO refueling station. Earth departure stages and their ship leave full for Mars.

Settings:

- 1) IN- Budget/Inflation: **Nominal** Purchase Power Scenario (Budget 1.175%/year, Inflation 2.5%/year)
- 2) IN- Post-ISS Scenario: **Nominal** Post-ISS Funding Scenario (\$1,750M/year available post-2024)
- 3) IN- Major Elements: Refueling stage / tankers, Mars Elements as “what-if” (defined only as \$ develop, make, etc.)
- 4) IN- Frequency of missions, every X years: **4.5**
- 5) OUT- Number of any launches per year, average: **7.1**
- 6) OUT- Number of tanker launches, per mission: **23**
- 7) OUT- Propellant (LO/LH) \$/kg: **\$4,200**

Observations:

The scenario again assumes the cancelation of the SLS/Orion programs, freeing up that funding into a major re-direction for NASA. Assuming the same Mars mission elements and their life cycle costs, the first mission to Mars occurs in 2030. NASA would need to collaborate with industry on tankers, a propellant depot in-space, commercial space operations, modifications to commercial crew spacecraft for cis-lunar capability, and Mars elements from habitats to landers and their Mars ascent (crew) vehicles.

As shown above, the scenario works not only with the nominal post-ISS funding scenario, but also with a near zero-post-ISS funding availability, opening the door to an assortment of other scenarios. These other scenarios could be merely margin for the scenario shown, a faster mission tempo (faster than every 4.5 years, re-approaching the 26 month DRA 5.0 cycles), extending mission stays on Mars, private sector space station partnerships, infrastructure on the Moon or Mars and others.

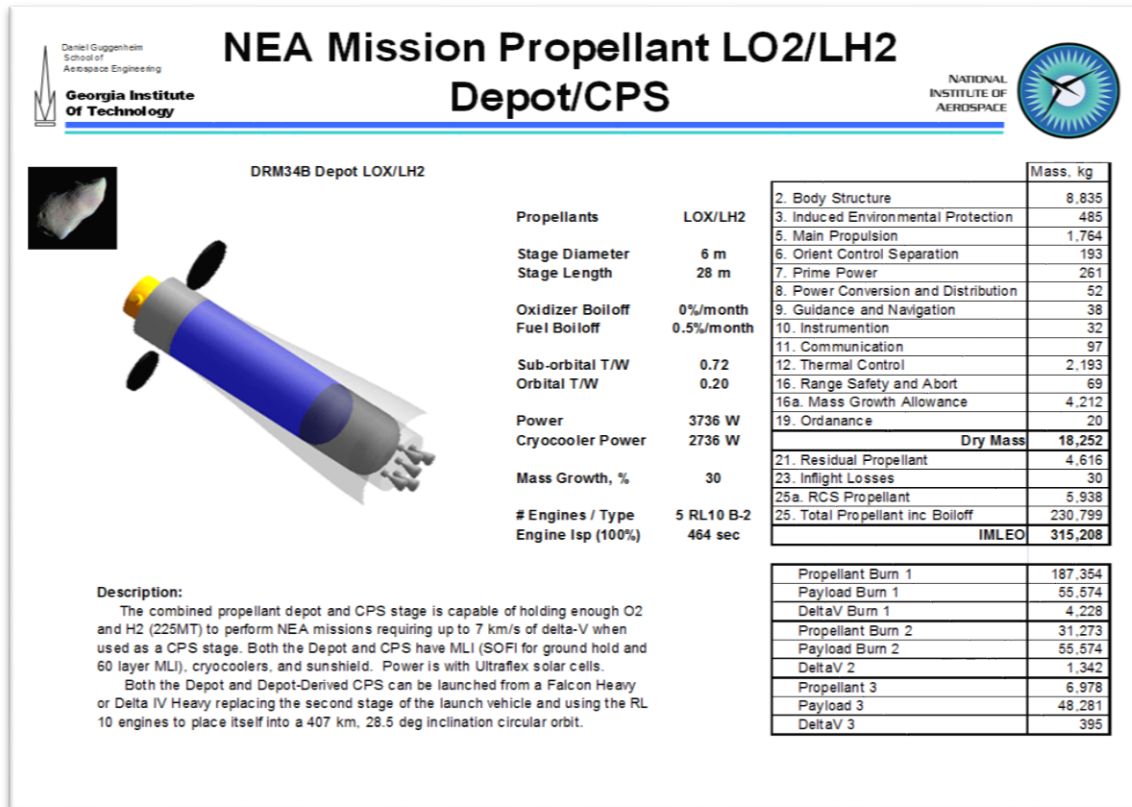


Figure 17: A Propellant Depot at a scale of an Earth departure stage applicable to a Design Reference Architecture 5.0 type Mars missions, among others²⁰. The commonality between a propellant depot and a cryogenic propulsion stage (CPS) would reduce their development costs while also having the basic manufacturing capability always active, through ongoing production of Earth departure stages, for when the depot requires replacement at the end of its design life.

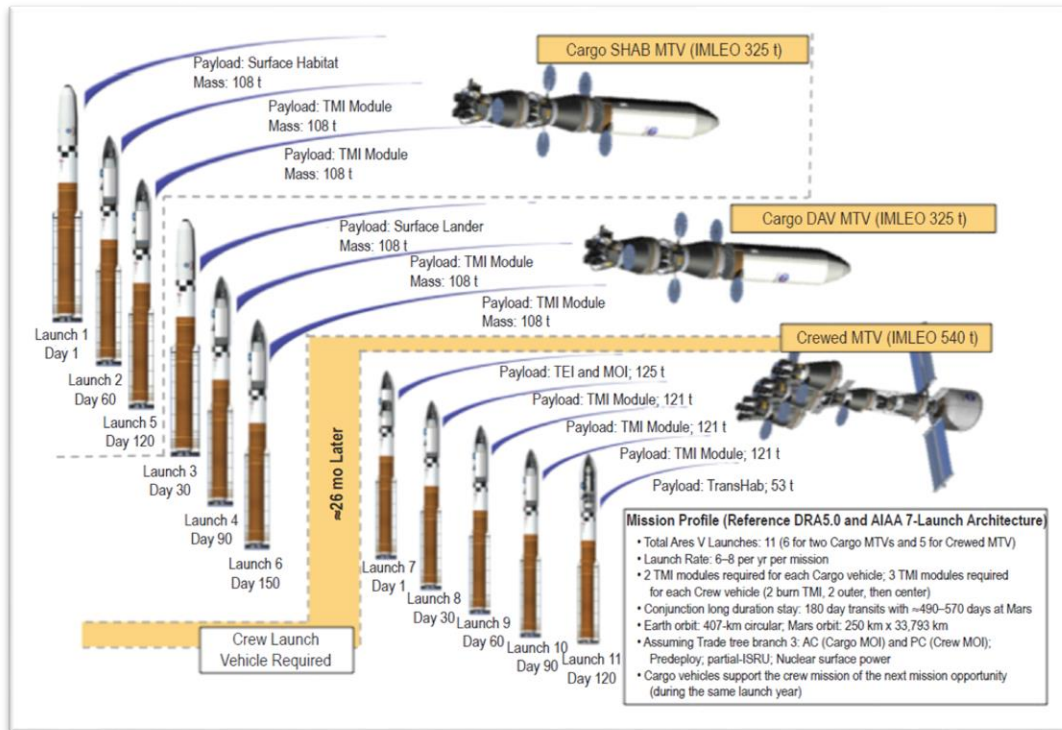


Figure 18. Example of using a smaller (EUS scale) upper stage as an Earth departure stage, for trans-Mars injection²¹. Though the surge approach to the launch scenario is not explored here, the basic cargo/crew ships and their tonnage inform the “What-if” Mars scenarios, but using a larger stage as in Figure 19.

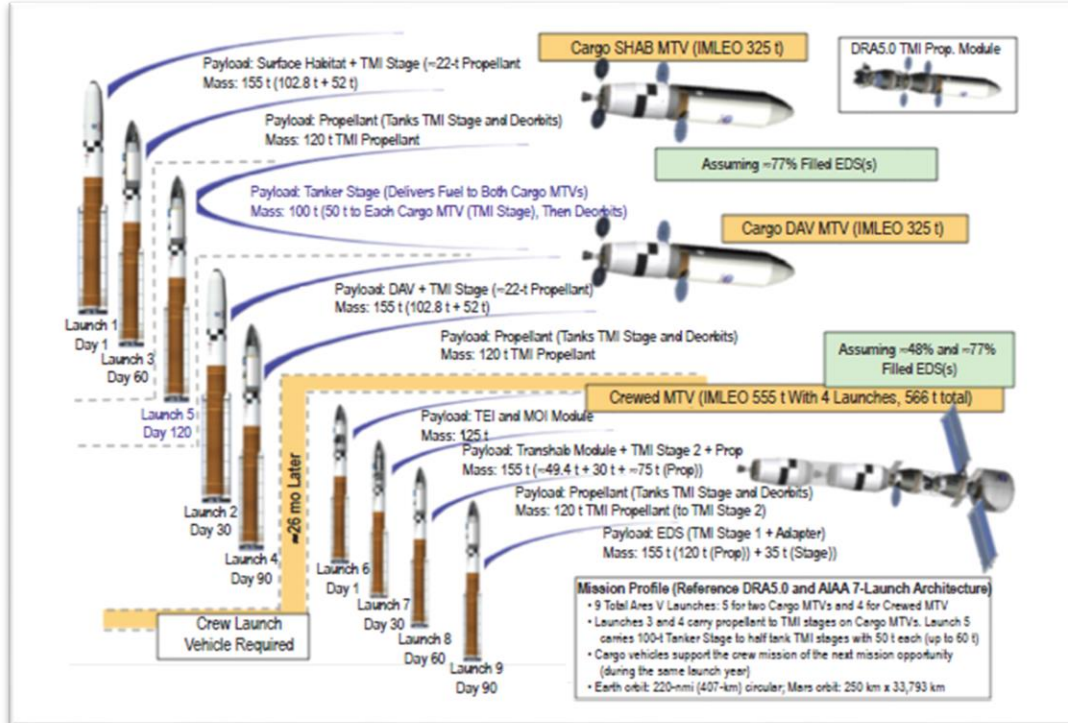


Figure 19. Example of using a larger upper stage as an Earth departure stage, for trans-Mars injection²². Note how now one stage replaces each of the two in each leg of the mission compared to Figure 18.

XIX. Points of Departure and Partnering

By way of addressing the importance of considering “how” NASA contracts, acquires or collaborates (a make, buy, or partner decision) for future space exploration, a return to the spacecraft data in Figure 5 alongside the Mars scenarios (Figure 15 and Figure 16) is necessary. Relatively recent experience with the NASA Commercial Orbital Transportation Services (COTS) / Cargo Resupply Services (CRS) acquisition approach showed the possibility of significantly lowering development and operational costs of complex space systems. The NASA Commercial Crew Program is also applying elements of this approach in its acquisition.

Across all the scenarios considered, multiple new elements will be necessary for NASA’s space exploration. Many of these new elements are cargo and crew spacecraft of some sort, as well as propulsion stages –putting aside the transportation of these to space or how these would depart Earth or it’s vicinity for the Moon or Mars. Minimally, these exploration elements would include-

- Landers, emplacing cargo, or a return / ascent spacecraft, for crew to leave a planetary surface
- Habitats in-space, for cargo as well as for crew, the “ship’s quarters” per se to Mars
- In-space exploration vehicles, much like crew spacecraft, but with additional flexibility
- More propulsion stages (for Earth departure, to return from Mars, etc.)
- In-situ Resource Utilization facilities on the Moon or Mars
- Rovers once on a planetary surface
- Habitats on a planetary surface, depending on the stay time
- And elements not yet envisioned or variants of the prior

Any ONE of these prior crewed elements, if it were to repeat a development cost close to Orion (a \$16 billion dollar procurement cost to NASA, development only, exclusive of other government management costs, through 2021, in 2015 \$ - Figure 5) would require-

- Over 5 Years of post-ISS funding in the high post-ISS available funding scenario
- Over 9 Years of post-ISS funding in the nominal post-ISS available funding scenario
- Over 10 Years of post-ISS funding in the low post-ISS available funding scenario

-with all the remaining elements yet to be developed.

Clearly, as with the elements such as landers in all scenario’s here, “how” an element is acquired by NASA, ranging from cost-plus to commercial, with other non-technical decisions (as a service, with redundant developers, as well as providers, aligning incentives) will be a cost driver in all exploration scenarios – lunar, asteroids, Mars or beyond. Traditionally, this was not an emphasis. Most NASA cost models ignore most costs, in the sense that there is little attention on the outcome of indirect partner costs, which are the majority of costs, or these are simply “wrapped” according to some rate after an emphasis on defining “what”, the technical factors such as a design, technology or requirements.

The basis of estimate of elements placed into some NASA purchase power and post-ISS funding scenario that can feasibly accomplish space exploration in relevant timeframes will by necessity have to place as much emphasis on outcomes about “how” (partner efficiency, innovation, and process/practices), if not more, than outcomes about “what” (design of elements). Evidence suggests that “what” does not have to drag or determine “how” and an army of labor costs, but rather that “how” should give rise to what” - the best design and specification is an output of an efficient and innovative set of processes and practices. The area of cost improvements possible requires more research. Initial indications are improvement factors for launcher developments, which should reflect on propulsion stages in general, such as Earth Departure Stages, are gains on the order of **>10X less development cost²³ to NASA, and prices for launch to NASA ~4-5X less than traditional**. These factors would be suspect if the only existence proof was a single launch system, but as shown in Figure 5, **similar improvement factors would apply to complex crew spacecraft**. SpaceHab, a program farther back, documented a similar improvement factor²⁴ (10X).

By the numbers, this prior observation is somewhat trivial. In the high post-ISS funding scenario there would be \$38 billion dollars in funding available through 2038 (2015 \$). A trivial observation is that this dollar amount cannot be spent on two cost-plus crewed spacecraft acquisitions (a crewed lander and a crewed habitat for example), leaving the rest undone. The more challenging question will be in locating the line where COTS/CRS-like or Commercial

Crew Program-like partnering may not achieve cost advantages in development and operations as with these prior programs. Locating that line is critical as a default decision to proceed with more traditional cost-plus acquisition strategies bakes a potentially unaffordable layer into already uncertain scenarios. *All* the points of departure for all the elements listed previously, must assume some more efficient acquisition process, closer to the COTS/CRS and Commercial Crew program experience, by default, undone only by actual experience to the contrary after forming element acquisition programs on this assumption (lack of viable partners, lack of progress on milestones, etc.).

XX. “All Our Models Say No” – and Recommendations

All the scenarios explored the possible edges of a scenario box, edges set by NASA’s purchasing power and NASA’s post-ISS presence in low Earth orbit. The scenarios also explored the potential contents of this box. Scenarios can-

- Change context: Make the box bigger, as in Figure 9, with a high purchasing power scenario, NASA budgets increasing on a par with any inflation, and the most possible post-ISS funding diverted to Mars exploration.
- Change content: Change what goes in the exploration box for Mars (or the Moon, etc.), canceling this or that program, redirecting to a new architecture, destination or approach. The record shows this has occurred at times²⁵.

Although scenarios other than baseline scenarios (SLS/Orion, etc.) were referred to as non-linear, it is arguable that both extremes, making the box far bigger, or dramatically changing what goes in the box, are equally non-linear – each is a challenging leap in its own way. Changing the edges of the box asks that NASA be isolated from the pressures of the federal budget, as well as many other factors (political, societal, demographic, etc.) affecting federal agencies. Changing the contents of the box is asking to disconnect NASA from past processes and relationships with industry and stakeholders, then reconnecting to new processes and relationships. Changing all the context asks the whole outside world to change, while changing all the content asks the whole world inside NASA to change.

In reference to just part of the elements of an exploration program beyond low Earth orbit, it has been noted that-

“All our models say ‘no,’ ” said Elizabeth Robinson, NASA’s chief financial officer, “even models that have generous affordability considerations.”²⁶

Making the box bigger would seem to have the benefit of being a choice supported by facts on the ground, existing facilities and programs. This is changing one variable, context, with contents unchanged. The option of changing contents would also have facts on the ground, budget outlooks, existing pressures and fiscal realities. This is changing one variable, contents, with context unchanged - accepting budget realities.

This begs the question marking the end of many a meeting – how to think outside the box? All the scenarios have assorted features in common that point to potentially significant answers here. As each bar in each scenario is a need for funds – how can NASA reduce the height of these \$ bars in any scenario while increasing its mission rate (cargo and crew yearly tonnage beyond Earth orbit) and expanding its capabilities (being in low Earth orbit, *and* the Moon, *and* Mars, *and* beyond)?

Significant, common factors offering significant improvements across *ALL* scenarios are-

1) Require all future Points of Departure for new elements be partnerships

As pointed out previously, and separately due to its importance, the Points of Departure of a future program, its starting assumption about the directions for the acquisition of multiple exploration elements from landers to injection stages, to insertion stages, to logistics modules and habitats, must begin with partnerships.

These partnerships should be similar to the recent ISS commercial cargo and crew programs. While there is no guarantee of repeating similar improvements in life cycle costs for new exploration elements, alternative Points of Departure that are more traditional (cost-plus, and related characteristics), baked into life cycle graphs via a basis of estimate, simply won’t fit any scenarios – even the most optimistic of high budget, low inflation, and high post-ISS funding.

Improvements in life cycle costs, from 10X to 5X, are a necessity *for starters*, in setting any initial content, the bars in the life cycle graphs, for any scenarios ahead, and such cost factor improvements have only been demonstrated when NASA undertakes commercial-like partnerships in acquiring goods and services. An emphasis on partnerships with significant cost improvements is consistent with staying ahead on the matter of purchase power, keeping the cost inflation rate within a purchase power scenario below any rate of budget growth – in effect increasing purchase power without the need for increased budgets. In addition, multiple partnerships as multiple providers can address risks from (1) the capacity limits of any one provider, avoiding exceeding any one provider's capacity, (2) element failures, reducing mission (campaign) risk where redundant launchers, spacecraft or services apply²⁷, and (3) misaligned incentives, creating a more competitive environment that aligns incentives near and far between NASA and providers.

While any particular new space system elements acquisition process may discover an initial lack of maturity in the ability of industry partners to develop and provide systems for NASA needs, this acquisition process would assume an investor mindset, rather than a purely engineering mindset. The acquisition process would consider the task of maturing industry capabilities as simply part of the process, the only means consistent with far term, dramatically improved, cost goals for the new elements required in NASA missions, if these are to achieve exploration outcomes in any budget scenarios.

2) **Require productivity goals that continuously go up, not down**

Reducing the height of any life cycle bars in a scenario, the \$ amounts, is possible by doing less. Mars design reference missions circa 2009/2010 studied crew departures to Mars every two years²⁸. In a paradigm of NASA yearly project budgets, it is not difficult to predict yearly costs – yearly costs are uncannily close to what funding an analyst knows may be available. The challenge in estimating costs is in calculating benefits. Cost are well constrained, benefits are to be determined. A benefit is a development's completion by some date, an operational capability sometime in the future, a flight, mission, milestone, acquisition or other rate capability achieved on a steady basis. Scenarios that reduce the productivity of content, such as missions to Mars every 4.5 years (Figure 15, Figure 16) to attempt to fit into a scenario box (budget, etc.), are heading the wrong way.

Pioneering is very distinct from exploring.

Explore: (as a transitive verb) 1a) to investigate, study, or analyze: look into, 1b) to become familiar with by testing or experimenting. 2) To travel over (new territory) for adventure or discovery. 3) To examine especially for diagnostic purposes. As an intransitive verb: to make or conduct a systematic search.

Pioneering: 1) being among those who first enter a region, in order to open it for use and development by others. 2) being one of a group that builds and prepares infrastructure precursors, in advance of others.

"Pioneering" life cycle cost scenarios must by definition be about developments and infrastructure in advance of others, permanence and growth, and not merely a visit. While some scenarios explored previously may set the stage for pioneering, by exploring, these scenarios do not directly address pioneering in our solar system.

Pioneering is consistent with taking the cost improvements pointed out previously as necessary, factors of 10X and 5X, even further. True pioneering scenarios have to push toward mission rates and capabilities measured in missions per year, not years between missions. While exploration paves the way for pioneering, pioneering by definition an evolution to a transition²⁹, away from government dominated activity to non-government and private sector entities. The costs and rate of the activity must be consistently improved to be consistent with eventual non-government, self-sustaining economic activities.

3) **Require NASA acquisitions to favor systems and partners that also grow non-NASA business**

Factor 1, partnerships, is consistent with the growth paradigm of Factor 2, pioneering and productivity. Combining these, the need to increase the tempo of systems being developed, manufactured and operated, may be achieved by integrating NASA mission needs alongside customers beyond NASA's limited government missions. Adding the requirement that systems and partners preferred by NASA be those systems and partners that mature private sector, non-NASA, business cases, other customers, opens the door to the life cycle improvements beyond factors of 10X to 5X required for pioneering. The amortization of fixed company costs, faster learning due to higher volume of manufacturing, or tempo of operations, and efficient company process/practices (competitive pricing), a requirement from the non-government customers, as incentive for the company business case, are all part of this factor, benefitting NASA's element acquisitions.

This economics acquisition strategy, setting a strong decision factor for selecting partners, for lowering the height of cost \$ bars in a NASA life cycle scenario while simultaneously increasing mission rate, will require an investment mind-set on the part of selecting officials. This is a necessary ingredient without which life cycle cost scenarios, merely by the numbers, and regardless of NASA budgets over the next generation, cannot conceivably pioneer the solar system.

4) Require increasing reusability of elements

Another path to lowering the height of cost \$ bars in a NASA exploration / pioneering life cycle scenarios, is not to add so many bars – for repeatedly making and launching things. Reusing an item already in space, not having to manufacture another unit, while also avoiding its launch costs, is a path to fitting more elements and their content into any budget scenarios, sooner. For Mars exploration scenarios candidates, habitats and related crew systems (the “ship” to Mars per se) should draw immediate attention for reusability, with the reuse of other elements from stages to spacecraft analyzed as well.

This item could especially benefit from Factor 1, partnerships, as control centers for more in-space activities with reusable elements, from traffic management to maintenance, would benefit from efficiencies akin to commercial satellite operations.

5) Develop refueling capabilities and infrastructure

A Mars exploration vessel, or other ships (lunar, asteroids, etc.), stages or landers, to increase reuse across more than one mission, would require refueling in some manner. This could be via intermediary depots or by direct transfer from tanker vessels. Given other potential uses, this direction would also offer paths consistent with Factor 3, favoring partner investments toward potential non-government business cases.

6) Mars (and the solar system) via the Moon, ISRU

Partnerships, increasing NASA mission rates, non-government business cases, reusability, and refueling may all come together in scenarios that push out into the solar system uses resources along the way. Lunar in-situ resource utilization (ISRU) could provide commodities such as LOX and LH2 to Mars missions assembling, preparing and refueling near the Moon. Reusable landers from the Moon, as tankers for lunar refueling stations providing propellant to Mars missions, might address Factors 3 (non-NASA business cases), Factor 4 (reusability), and Factor 5 (refueling).

XXI. Conclusions

This analysis has demonstrated the possibilities and importance of merging context and content, made possible via cost modeling and scenario analysis. This has been about numbers, estimated costs and budgets, and how these may add-up, or not, in diverse NASA space exploration scenarios. It is also about scenario planning, showing a way to avoid the tension between the details and numbers for specific paths and being overwhelmed when stepping back to consider all the possibilities.

Future applications will mature this capability and develop more scenarios, emphasizing the recommendations that emerged from looking across the multi-verse of possible scenarios for NASA and its future in space exploration.

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